Technical Memo

ANL/EES-TM-279

AN ASSESSMENT OF SOLAR HEATING SYSTEMS WITH SEASONAL STORAGE IN NEW ENGLAND

Systems Using Duct Storage in Rock and a Heat Pump

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Systems Using Duct Storage in Rock and a Heat Pump

by

Dwayne S. Breger* and Allan I. Michaels

Energy and Environmental Systems Division
Solar Energy Section

January 1985

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Assistant Secretary for Conservation and Renewable Energy
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AN ASSESSMENT OF SOLAR HEATING SYSTEMS WITH SEASONAL STORAGE IN NEW ENGLAND

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ABSTRACT

This report assesses seasonal storage of solar energy for the New England region, using duct storage in rock and a heat pump. The winter climate in New England requires large heating loads, and the winter insolation is inadequate for significant solar contributions from diurnal or passive systems. The abundant solar energy available during the remainder of the year could be of great value if coupled with a seasonal storage facility. Analyses are performed for flat plate and unglazed collectors, for low- and high-temperature load demands, and for various locations in New England. A heat pump is used in the system to reduce the storage temperature, thereby increasing collector efficiency and reducing losses. The results of the analysis indicate that in the optimized systems solar energy could provide 75-80% of the low-temperature demand load and 60-65% of the high-temperature demand load, with the remaining portion coming primarily from the heat pump's electrical-energy input. The annual cost of the energy supplied by the system to the distribution network (using the base-case economic scenario) is \$44-52/MWh and \$58-62/MWh for the low- and high-temperature loads, respectively. Significant reductions in cost are attained when systems are financed using present incentives provided by the federal government.

1 INTRODUCTION

This assessment has been conducted as part of the United States effort in the International Energy Agency (IEA), Solar Heating and Cooling Program, Task VII on Central Solar Heating Plants Using Seasonal Storage (CSHPSS). The objective of this study is to assess the potential of CSHPSS in the New England area. The technology under consideration involves the collection and seasonal storage of solar energy to provide space heating and hot water. The study concentrates on the use of duct storage in the bedrock so prevalent in New England. The storage system consists of deep vertical boreholes through which heat is transferred to the bedrock from the collector array and from the bedrock to meet the load. The temperatures throughout the collection and storage systems remain relatively low to improve performance and efficiency. A heat pump is used to condition the heat to a temperature adequate for the load.

Subtask II(b) of IEA Task VII involved the evaluation of CSHPSS systems based on the three main storage technologies.[1-4] The "water" team studied storage systems using constructed water volumes -- tanks, rock caverns, or water pits. The "aquifer" team evaluated storage in underground aquifers. The "duct" team evaluated storage in either clay or rock of heat transferred through boreholes within the heat-storage medium. Comparison of the results among storage types indicated that systems with heat pumps could supply heat at the lowest unit cost, with solar energy generally displacing 70-75% of the load and the heat pump's electrical input providing the remainder. Systems without heat pumps would displace over 90% of the load by solar energy, but at higher unit cost.

A general ranking by storage type of the three systems' cost-effectiveness showed aquifers having the lowest unit energy cost, followed by ducts and then by water; however, site variations and uncertainties in storage costs would tend to reduce the importance of the ranking. Aquifer storage is very dependent on the presence of an aquifer that is suitable both in terms of its hydrogeological characteristics and in terms of the legal and regulatory aspects governing usage of the water resource. Water storage in tanks and pits offers the most widely applicable technology. Water pits require suitable soil characteristics, but such pits are an attractive option in all cases, especially at higher storage or demand temperatures. Duct storage gives very favorable results, but its dependence on the soil and rock conditions of the site is a possible limitation.

The overall results of the IEA Task VII CSHPSS-system evaluation showed that these systems may often be a cost-competitive option. The international effort was based on the best "average" system parameters and cost data; therefore, the results cannot be applied directly to a specific site or economic situation. It is clear, though, that the results have demonstrated lower solar-energy unit cost for CSHPSS systems than for any other solar technology used to provide space heating (particularly in the case of systems designed to displace significant portions of large loads).

Seasonal-storage systems are based on large loads, with heat stored and distributed from a central storage facility. Solar collectors can be placed beside or (often) on top of the storage facility or the buildings to be served. The load size must be large and dense (in terms of energy per unit of land area) to provide economies of scale for the storage and distribution system. A large storage is also necessary to reduce heat loss to a small fraction of the total heat stored. The seasonal-storage concept allows the collectors to operate efficiently throughout the year and make use of all the solar energy available -- especially the most intense radiation in the summer, when collection can be done very efficiently with conventional flat plate and unglazed collectors. The most attractive loads are based on low demand temperatures, which can be used for residential multifamily or community housing developments, shopping areas, business parks, etc.

Duct storage was chosen as the basis for this assessment because of its low cost and the prevalence of accessible bedrock in New England. The only substantial experience with storage in rock is in Sweden, where most of the conceptual and technical development has taken place amid continued interest.[5] Only systems equipped with heat pumps are considered here; an actual design effort should also analyze designs without heat pumps that might be advantageous under certain site or load conditions and electricity rate structures. Generally, though, the Subtask participants' work indicated that the lower temperatures and better efficiencies obtained with a heat pump (at temperatures adequate for good heat-pump coefficient of performance [COP]) provided the most cost-effective designs. However, systems without heat pumps could supply a larger portion of the load with solar energy.

The duct storage system is constructed using conventional well-drilling technology. A matrix of boreholes is drilled to create a heat exchanger within the rock. The rock should not be greatly fractured, and water movement through the storage region must be small. Suitable characteristics are commonly found in New England bedrock. Generally, fracturing decreases with depth, and water movement is small in level areas (correlated with small water-pressure gradients). Rock above or below the water table can be suitable. Initial site studies must be performed to determine the suitability of the local geology. Other storage options need to be assessed in this early phase of the design. A description and discussion of duct rock storage, published by IEA Task VII in Phase I (see Ref. 5), is included as App. A. This account provides information not included here.

2 CONDITIONS IN NEW ENGLAND

2.1 CLIMATIC CONDITIONS

The New England climate is characterized by four distinct seasons. The insolation during the summer is comparable with that in most of the rest of the United States; the winters are cold, and insolation is low compared with that in other regions of the country. The large space-heating loads are particularly difficult to displace with diurnal solar systems, or even with passive architecture. The relatively cloudy New England winters are in sharp contrast to the conditions in the western, mountainous regions of the U.S., which have similar heating loads but benefit from a relatively large amount of direct solar radiation during the winter. The ambient winter temperatures in New England do not exhibit the extreme lows that characterize the north-central regions of the U.S. (e.g., Minnesota).

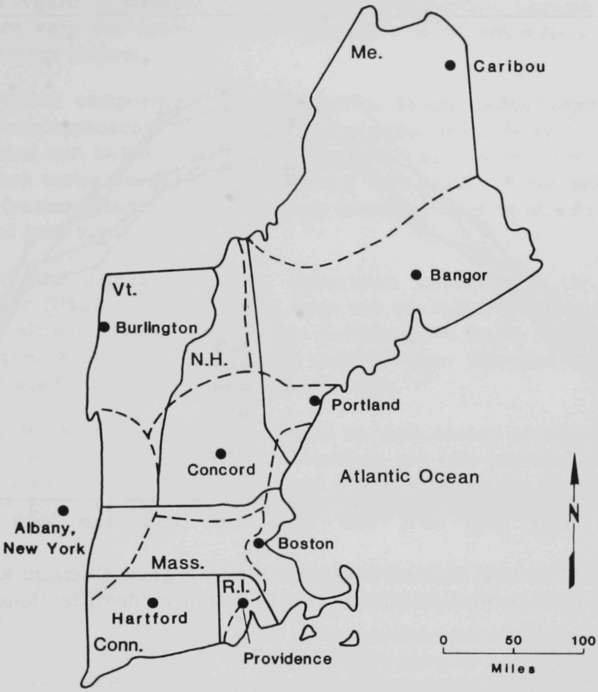
Within New England, a degree of variation is also present. Figure 1 depicts geographical regions of New England characterized by climatic conditions that correspond approximately to those found in selected cities within the regions. The figure also indicates typical heating-season conditions and insolation quality for the regions. The insolation and ambient-temperature conditions for these climatic regions are shown in greater detail in Figs. 2 and 3, where the figure keys indicate climatic regions in terms of symbols and acronyms used for the representative cities; the cities and their acronyms are as follows:

- Hartford, Connecticut (HAR)
- Bangor, Maine (BAN)
- Albany, New York (ALB)
- Burlington, Vermont (BUR)
- Concord, New Hampshire (CON)
- Boston, Massachusetts (BOS)

Data used in Figs. 2 and 3 are taken from the National Climatic Center, Asheville, North Carolina. They are Typical Meteorological Year (TMY) data, from the Region 1 Tape.

2.2 GEOLOGICAL CONDITIONS

The present geology of New England dates back to the retreat of the glaciers during the last ice age. The area includes long coastal regions, as well as mountain ranges in western Massachusetts, central New Hampshire, and Vermont. Bedrock close to the earth's surface is prevalent throughout the area, with the exception of the Boston Basin (a region of about 20 miles radius, centered on Boston) and Cape Cod. The exact



REGIONAL CHARACTERISTICS

City/Region	Ambient Conditions during Heating Season	Insolation
Hartford, Conn. (HAR)	rather cold	medium/low
Boston, Mass. (BOS)	rather cold	medium/good
Albany, N.Y. (ALB)	quite cold	very good
Concord, N.H. (CON)	quite cold	low
Burlington, Vt. (BUR)	very cold	very good
Bangor, Me. (BAN)	very cold	good
Caribou, Me.	extremely cold	good

FIGURE 1 New England Climatic Regions and Regional Characteristics (TMY data available for cities shown on map)

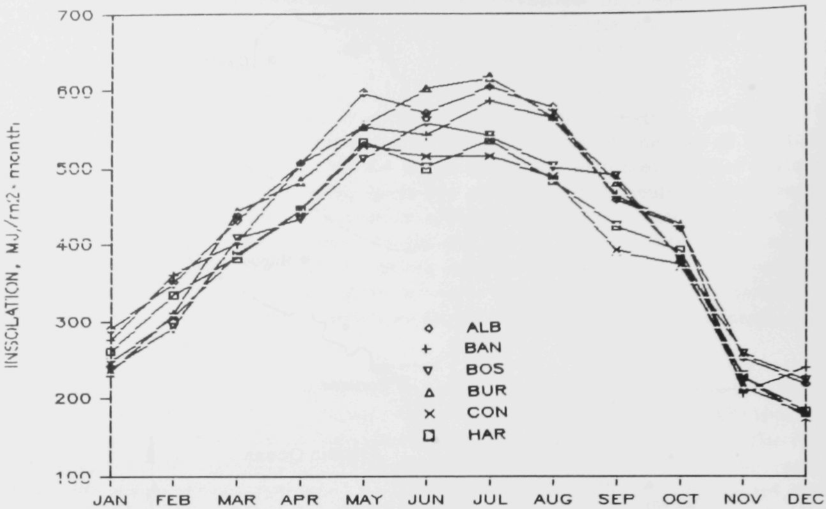


FIGURE 2 Total Monthly Incident Insolation in New England Climatic Regions (collector tilt angle equals latitude; see text for acronym identifications)

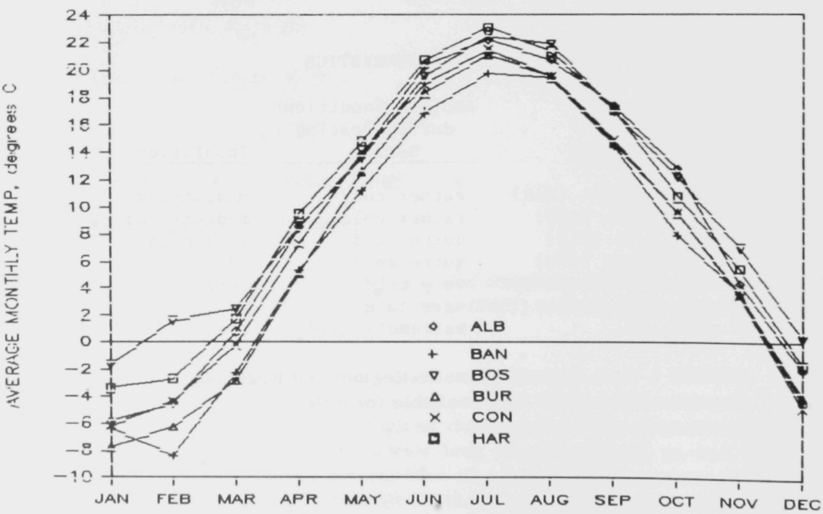


FIGURE 3 Average Monthly Ambient Temperature in New England Climatic Regions

conditions with regard to surficial layers, bedrock composition, bedrock fracturing, and water tables are very site-specific. An exploratory study would have to precede any specific heat-storage project.

The bedrock composition includes granite, felsite, metamorphized shale, and sandstone. As one approaches the mountainous regions, the bedrock is commonly found to be quite folded and twisted from the past glacial movements. The extent of fracturing in the rock varies considerably, decreasing with depth. Water movement through the paper-thin fractures and across the storage boundary must be small so as not to be a serious source of heat loss.

Most of the populated regions have been surveyed by the United States Geological Survey (USGS), and geological maps are available from which specific sites can be studied initially. Maps indicate the surficial-layer depth, bedrock composition, and hydrogeological conditions. An average surficial-layer thickness of 6 m (20 ft) was deemed appropriate for the purpose of a generic study.[6,7]

In many areas, the surficial layer would be thick enough to consider an earth-pit storage facility as a design alternative. Aquifers are also prevalent in many areas, though water movement tends to be significant and competition for the water resource is both intense and subject to strict and extensive regulatory requirements.

2.3 ECONOMIC DEVELOPMENT

Despite an overall population shift to the southern and southwestern areas of the United States, the economic health of the Northeast remains strong, and many areas of new development are in evidence.[8] Most of the new development is going on outside the main cities, where less restrained land area is available for potential CSHPSS systems. Many new office and multifamily-housing units have been built or are in the planning stage, so retrofit applications are important.*

The cost of energy in the Northeast is the highest in the country. All oil and natural gas products consumed are brought into the local New England economy from outside.

*A useful guide to development activity in the area is the *New England Real Estate Journal.*

3 SYSTEM ANALYSIS AND DESIGN

3.1 ANALYTICAL METHODOLOGY

The analysis has been performed using the MINSUN Version III computer-simulation model with the DST (duct storage) option.[9] The simulation was used to determine system performance over a range of important design input parameters. The system performance was first studied by itself; results are presented in Chapter 4. A set of economic scenarios (described in Chapter 5) was applied to the range of system designs and performance characteristics simulated by MINSUN to determine the system economics and cost-effectiveness. Preceding the actual analysis, several preliminary analyses were performed to define the appropriate range of input parameters and set other parameters to fixed values in order to reduce the analytical complexity.

The scope of the analysis is indicated in Fig. 4, where the base-case scenario is specified by characteristics listed above the dotted line. Each component variation is also analyzed in combination with the remaining base-case components.

3.2 SELECTION OF SYSTEM PARAMETERS

The input-parameter file for the MINSUN simulation is given in Figs. 5a and 5b. The analysis for each scenario was performed by investigating the influence on performance and economics of the following design parameters:

- Collector type
- Collector area
- Storage volume
- Storage (borehole) depth
- Number of boreholes
- Heat-pump evaporator heat-transfer capacity

The parameters used to describe the two collector types, the two load demand temperatures, and the borehole design are detailed in Table 1 and Figs. 6 and 7. Information on collector performance and cost was obtained through previous IEA Task work and through direct contact with North American manufacturers.[10] The analysis does not take into account the presence of a distribution system, but only the heat supplied to an assumed distribution system. The thermal losses and cost of the distribution component are highly dependent on load density, distance of load from the solar plant, distribution temperature, and retrofit conditions. The results of the analysis, therefore, are correctly understood to be for the heat supplied to the distribution system.

System Design Components

TMY DATA	LOAD	COLLECTORS	STORAGE	HEAT PUMP
Hartford, Conn.	Residential (500 unit), Low-Temperature	1) Unglazed	Duct in Rock	with Heat Pump
Bangor, Me.	Residential (500 unit), High-Temperature	2) Flat Plate		
Albany, N.Y.				
Burlington, Vt.				
Concord, N.H.				
Boston, Mass.				

FIGURE 4 Scope of Analysis (base-case characteristics listed above dotted line)

Figures 8 and 9, derived from the collector characteristics, show collector performance vs. inlet temperature for the various New England locations. Collector performance is quantified by the total energy collected during the TMY at a given constant inlet temperature. Unglazed collectors show much greater degradation of performance as operating temperature increases. Hartford, Connecticut, was selected as the base-case climate, because the collector performance and the ambient temperatures during the heating season there were closest to the average among all the locations.

```
*  NUMBER OF     THERMAL       HEAT       LAYER      STARTING TEMP.   MAX TEMP
*  LAYERS IN     CONDUCT.   CAPACITY  THICKNESS    AT TWO NODES     CHANGE IN
*    GROUND      (......FOR EACH LAYER........)                     YEAR (C)
*
      2       1.9   2.16E6  6.1     3.0  2.1E6  300.     15.     15.       5.
*
PERIOD
*       FIRST DAY      LAST DAY          OF HEATING SEASON
*                                      (FROM BEGINNING OF YEAR)
        274             135
*
HOUSELOAD AND DISTRIBUTION
* NUMBER OF   WITH   K-       INDOOR  OPTION   OPTION  FEED TEMP HOUSE
* HOUSES      AREA   VALUE     TEMP   WAY      RETURN  EKV. PARAMETERS
*              M2    W/M2/K    C                        C         C    C
*
   500.       350.  .686      18.     3          1      55.  0.5  0.   35.
*
* HUMAN     TAPWATER  HOUSELOAD  INSULATION  PIPE
* POWER     POWER     NETWORK    THICKNESS   DIAM
*                     LENGH
* W/HOUSE   W/HOUSE     M            M         M
*
   400.      460.       0.         0.01        0.1
*
HEATPUMP
* IPAR    ETA    TBROK    TSTAG    TFMIN     MIN     EVAKT    CONDKT
*                  C        C        C       COP     KW/K     KW/K
*
  1     .60       50.     100.      5.        1.      500.    300.
*
COST *** COST SCENARIOS DESCRIBED IN SECTION 5 ***
* COLLEC ASYMPT. SPECIFIC   SIZE    BETA DEPTH GAMMA BOREHOLE GROUND INSULATN
*  TOR   STORAGE FOR SMALL  OF SML       COST           COST
*                STORAGE    STORAGE      EXP
*  $/M2    $/M3    $/M3       M3          /M            $/M      $/M2      $/M3
*
   245.     0.1     0.2     10000.   0.1  1.0    1.0    15.     0.0      100.
*
*CONDEN EVAPO HEAT PUMP   INST DIM    AREA    LENGTH PIPE   AUX HOUSE FUEL
* SER   RATOR EL MOTOR    REF  EXPO   DISTRI  DISTRI INSULA  HEATING
*             INSTALLED   POWER NENT  BUTION  BUTION  TION   INSTALLED
* $*K/W $*K/W  $/W         MW          $/M2    $/M     $/M3    $/W     $/KWH
*
   .2    .2    .2         0.6  -0.3     0.     250.     0.     0.1     0.05
*
* ELCOST  DEPRECIATION  INTEREST  REAL INCREACE
*         TIME                    ENERGY PRICE
*  $/KWH  YEAR          PER CENT  PER CENT
   0.05    20.            5.        2.
*
REPORT OPTION
    2
END
```

FIGURE 5a Input-Parameter File for MINSUN Simulation, Page 1

```
 DUCT STORAGE INPUT OPTIONS FOR CSHPSS NEW ENGLAND ASSESSMENT
  REPT
*
INSULATION
* COLL NETW     EARTH      DIAM          FIX
* INSULATION    TEMP       DEPENDENT     INSULATION
* COND                     INSUL
*   W/M/K         C          M              M
*
     .04         10.        0.1           .02
*
COLLECTORS
* OPTION          AREA   TEMP   DTMAX    TMAX1   DUMMY   TMAX2   NORMAL    MAX
* 3 FOR IEA              STEP                            TEMP     FLOW     FLOW
* OPTION
*                  M2     C                                C    KG/S/M2  KG/S/M2
*
   3             15000.   0.0    10.      20.     0.0     97.    .015      .1
*
* NETWORK     INSUL    PIPE
* LENGTH      THICK    DIAM
*             NESS
*  M           M         M
*
  300.        0.0     .30
*
STORAGE
* VOLUME        DEEP        NUMBER     RADIUS       THICKNESS          THERMAL
*                               OF                      OF         CONDUCTIVITY
*                           BOREHOLES             INSULATION       OF INSULATION
*   M3           M                       M              M              W/M.K
 400000.      106.1          800      0.1524           .0               .05
*
*     OPTION           SIDE COVER        DISTANCE         THERMAL
*      1/2/3           (OVERLAY FR.      GROUNDLEVEL/     COND. OF
* COVER/OVERLAY/NO      OF HEIGHT)       STORAGE          STORAGE
*     M2.K/W                                 M              W/MK
*
      2                   0.1              6.1              3.0
*
*    THERMAL                MAX DURATION              MAXIMUM
*  RESISTANCE                                         STORAGE
*  FLUID/SOIL                                          TEMP
*   M2.K/W                       YRS                     C
*
     0.01                         2                    100.
*
*     NUMBER          MAXIMUM MEAN      MAX DIFF         START SURFACE    TEMP GRAD
*       OF            STORAGE TEMP    BETWEEN PRE-            TEMP         GROUND
*  PRE HEATING        DURING PRE-     HEAT MAX &
*     CYCLES          HEATING  (C)    ACTUAL MAX               C             C/M
*                                       TEMP (C)
      2                 50.               5.                  10.           0.02
*
```

FIGURE 5b Input-Parameter File for MINSUN Simulation, Page 2

TABLE 1 Description of Collectors[a]

Collector Type	Intercept	Slope ($W/m^2 \cdot K$)	Array Effect
Flat Plate	0.800	4.5	0.66
Unglazed	0.778	15.0	0.70

[a]Latitude tilt, with an incident-angle modifier of 0.1.

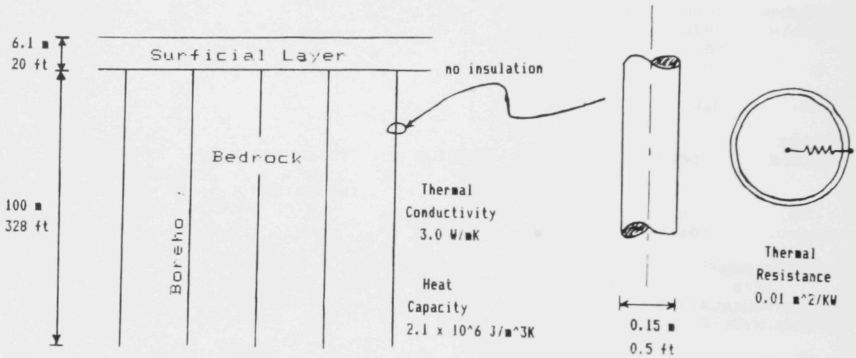


FIGURE 6 System Parameters for Storage System

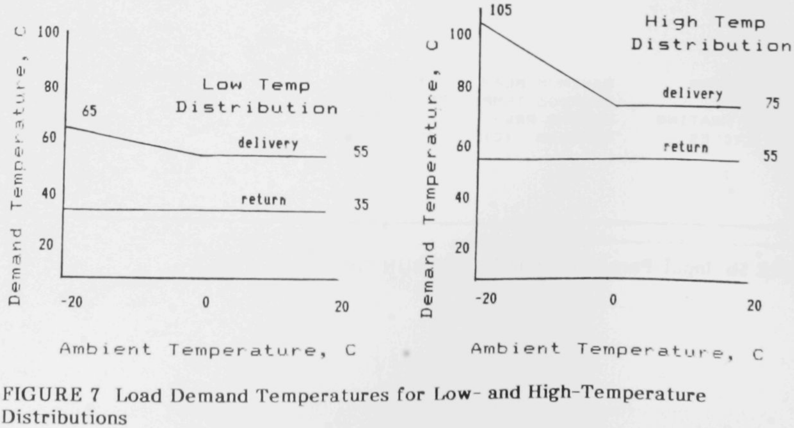


FIGURE 7 Load Demand Temperatures for Low- and High-Temperature Distributions

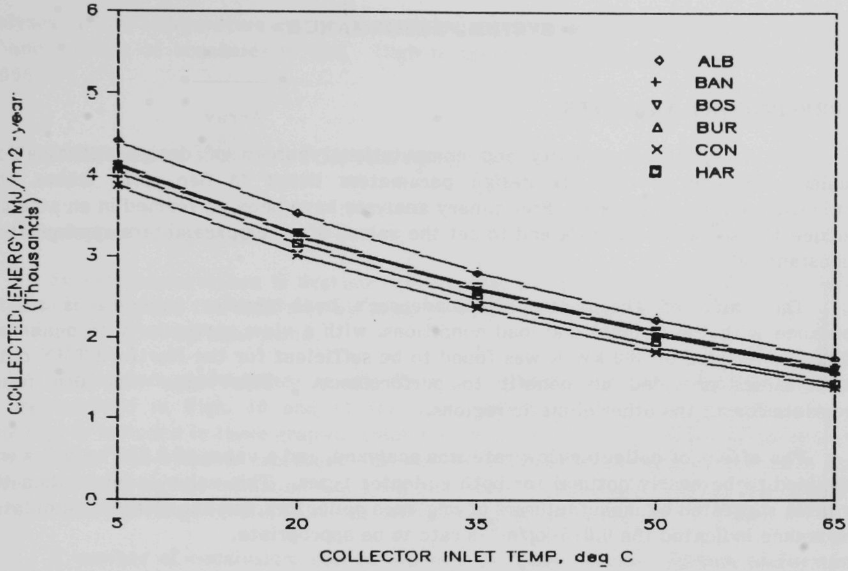


FIGURE 8 Performance of Flat Plate Collectors in New England Climatic Regions

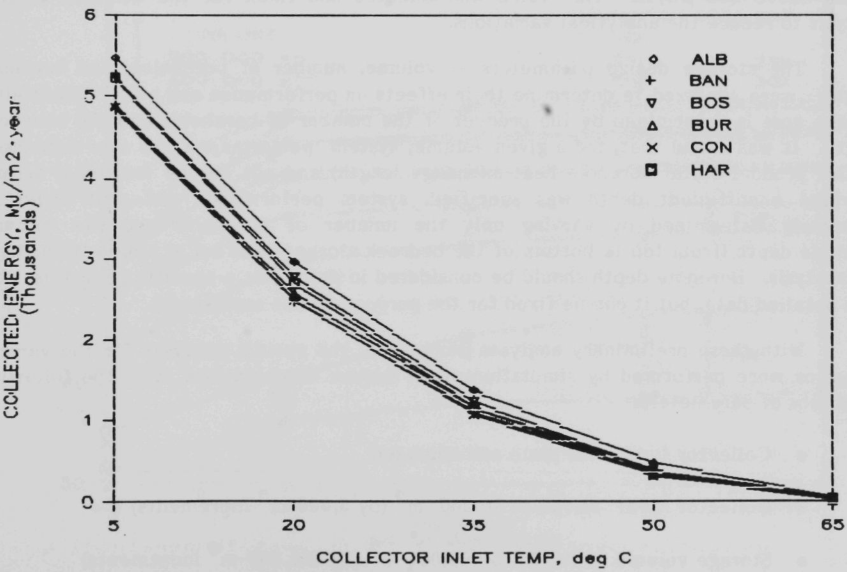


FIGURE 9 Performance of Unglazed Collectors in New England Climatic Regions

4 SYSTEM PERFORMANCE

4.1 PRELIMINARY ANALYSES

The analytical complexity and computational burden of design optimization, including variation of the six design parameters listed in Sec. 3.2, makes this optimization a very large task. Preliminary analyses have been performed in an attempt to reduce the scope of this task and to set the values of other parameters appropriately (at constant values).

The value of the heat-pump condenser's heat-transfer capacity is set in accordance with the climate and load conditions, with a view particularly to peak load conditions. A value of 300 kW/K was found to be sufficient for the Hartford TMY data; greater values provided no benefit to performance. This value was also found appropriate for all the other climatic regions.

The effect of collector flow rate was analyzed, and a value of 0.015 kg/m^2·s was determined to be nearly optimal for both collector types. This value is lower than the flow rates suggested by manufacturers of unglazed collectors, but the MINSUN simulated performance indicated the 0.015-kg/m^2·s rate to be appropriate.

The heat-pump evaporator's capacity was found to have a marginally decreasing beneficial effect on performance as its value increased. The magnitude of this performance benefit, in terms of annual solar fraction, became very small for parametric values above 500 kW/K. This value was selected and fixed for the duration of this analysis to reduce the analytical variations.

The storage design parameters -- volume, number of boreholes, and borehole depth -- were analyzed to determine their effects on performance and cost. Essentially, storage cost is determined by the product of the number of boreholes and the borehole length. It was found that, for a given volume, system performance was also dependent on this product (total borehole heat-exchange length) and not on the individual terms. Provided a sufficient depth was specified, system performance and cost could be accurately determined by varying only the number of boreholes and the volume. Borehole depth (from top to bottom of the bedrock storage) was set at 100 m throughout the analysis. Borehole depth should be considered in detail for a specific geological site with detailed data, but it can be fixed for the purpose of this assessment.

With these preliminary analyses completed, the system analyses for the various scenarios were performed by simulation of all system combinations, with the following variations of parameters:

- Collector type: flat plate and unglazed
- Collector area: 10,000 to 30,000 m^2 (by 5,000-m^2 increments)
- Storage volume: 200,000 to 600,000 m^3 (by 100,000-m^3 increments)
- Number of boreholes: 200 to 1000 (by 200-hole increments)

Analyses of low-temperature systems other than the base case limited volume to 500,000 m^3 and number of boreholes to 800. High-temperature analyses extended the area to 35,000 m^2.

4.2 PERFORMANCE RESULTS FOR THE BASE CASE

4.2.1 Basic Performance Results

System performance is best summarized by the system's solar fraction, defined as the percentage of the load met by solar energy. The solar fraction does not include the energy put into the heat pump.

The system performance results from the MINSUN simulation for the base case are summarized in Figs. 10 and 11 for both collector types. Every parameter set simulated is included in these graphs, which plot solar fraction vs. number of boreholes in the storage. The symbols represent the various collector-area values. For each area, curves representing the minimum and maximum solar fraction are drawn. The spread of points within the range results from variations in storage volume.

A number of conclusions can be drawn from these results. System performance increases with the number of boreholes, but the marginal increase declines and becomes

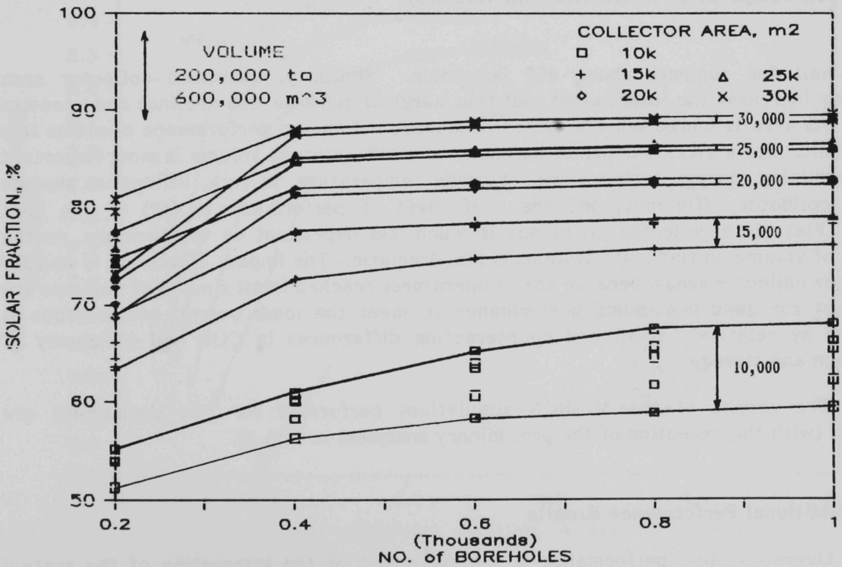


FIGURE 10 Base-Case Performance Results Using Flat Plate Collectors (Hartford, Conn.; low-temperature distribution; all volumes)

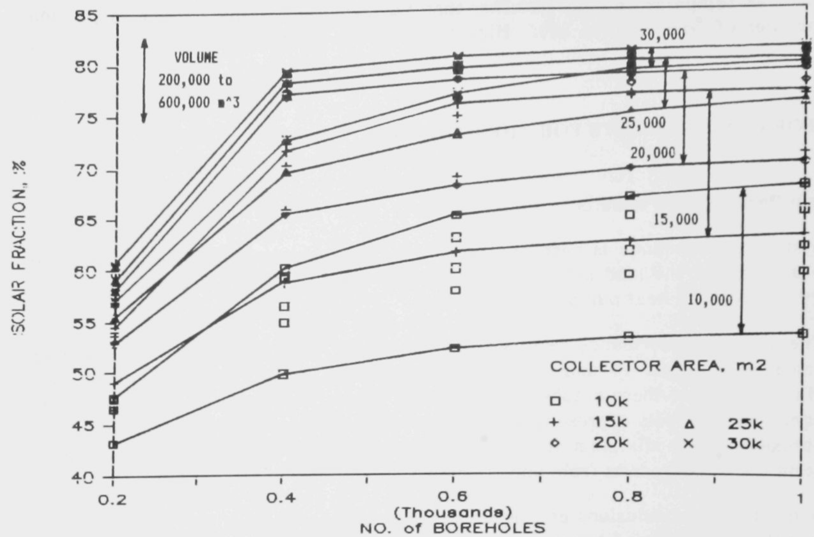


FIGURE 11 Base-Case Performance Results Using Unglazed Collectors (Hartford, Conn.; low-temperature distribution; all volumes)

very small for numbers above 600 boreholes. Similarly, increased collector area certainly increases the solar output, but this marginal increase also declines and becomes small. As area is increased, the effect of storage volume on performance becomes less significant. For a given number of boreholes and area, storage volume is most important in determining storage temperature. Storage temperature, in turn, influences storage losses, collector efficiency, and the coefficient of performance (COP) of the heat pump. Flat plate collector efficiency is much less dependent on temperature, so the impact of volume on flat plate systems is less dramatic. The impact of volume is smaller for larger collector areas, because the temperatures reached in all simulated volumes are sufficient for good heat-pump performance to meet the load; overall performance is affected by relatively small and counteracting differences in COP and efficiency of collection and storage.

The results of the MINSUN simulations performed for this assessment are included (with the exception of the preliminary analyses) in App. B.

4.2.2 Additional Performance Results

Overall system performance is the net result of the interaction of the system components -- particularly the collector, storage, and heat-pump subsystems. In this section, the effect of certain design parameters on subsystem performance criteria is analyzed. To simplify the graphical and conceptual presentation, some design parameters were held constant in order to study the effects of the others. A design term called the borehole density -- the total borehole length (number of boreholes times borehole depth) per unit of storage volume -- is derived. This term is important in terms of the storage temperatures and heat-exchange effectiveness.

The subsystem performance is presented in Figs. 12-15, which are derived from system simulations for Hartford, Connecticut, based on flat plate collectors (collector area of 15,000 m^2) and a low-temperature demand. The collector area is fixed so that the effect of volume and number of boreholes (or borehole density) can be studied. A change in collector area, with all other parameters fixed, would have a relatively direct effect on the results.

Figure 12 shows the collector performance in terms of the solar energy collected and stored, while Fig. 13 shows the storage performance in terms of the maximum temperature attained during the year and the storage heat loss. In these two figures, the symbols associated with particular curves denote particular values of storage volume. For a given volume, collector performance benefits from having a larger number of boreholes (due to the better heat-exchange characteristics). Larger volumes have a more pronounced beneficial effect (due to the lower average temperatures at which the systems operate), thus providing better collector efficiency. This decrease in the storage operating temperatures is apparent in Fig. 13. Heat loss is quite small for these large

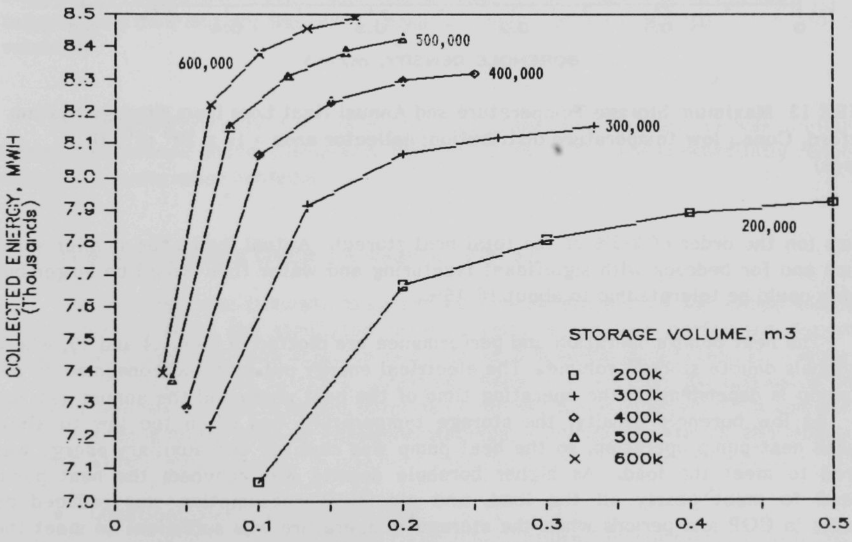


FIGURE 12 Flat Plate Collector Performance Results (Hartford, Conn.; low-temperature distribution; collector area = 15 x 10^3 m^2; all volumes)

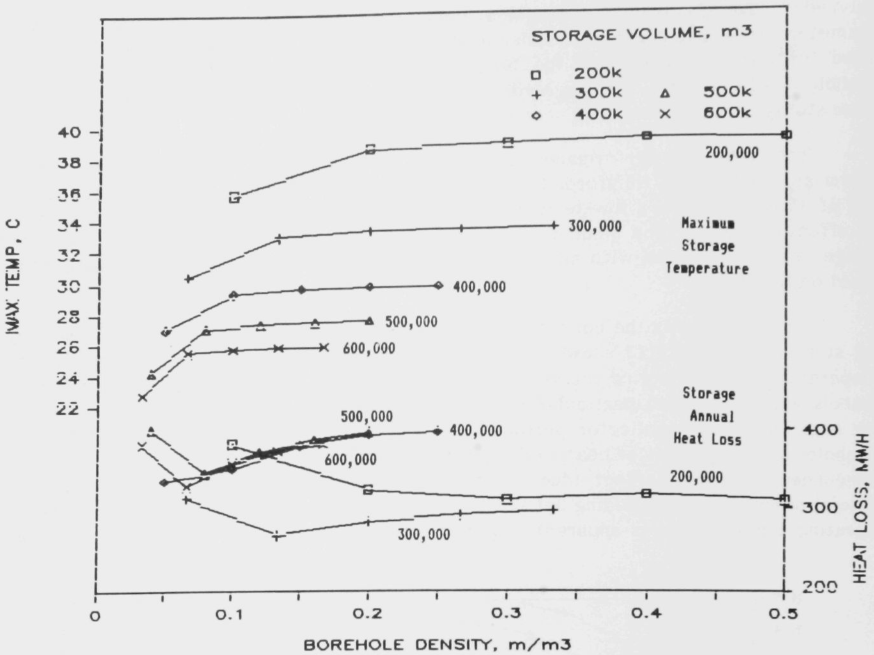


FIGURE 13 Maximum Storage Temperature and Annual Heat Loss from Storage System (Hartford, Conn.; low-temperature distribution; collector area = 15 x 10^3 m^2; all volumes)

systems (on the order of 3-5% of the total heat stored). Actual losses for smaller-scale systems and for bedrock with significant fracturing and water flow would be larger but probably could be tolerated up to about 10-15%.

The heat pump's operation and performance are plotted in Figs. 14 and 15, where the symbols denote storage volume. The electrical energy put into and consumed by the heat pump is dependent on the operating time of the heat pump and the annual average COP. At low borehole density, the storage temperature was often too low to allow adequate heat-pump operation, so the heat pump was shut off and auxiliary energy was required to meet the load. As higher borehole density was reached, the heat pump operated to meet nearly all the load, and electrical consumption was reduced by increases in COP and periods when the storage temperature was sufficient to meet the load directly. For a given number of boreholes, smaller volumes provided somewhat better COPs (due to higher temperatures), but the heat pump's operating time was reduced because of the smaller amount of heat stored.

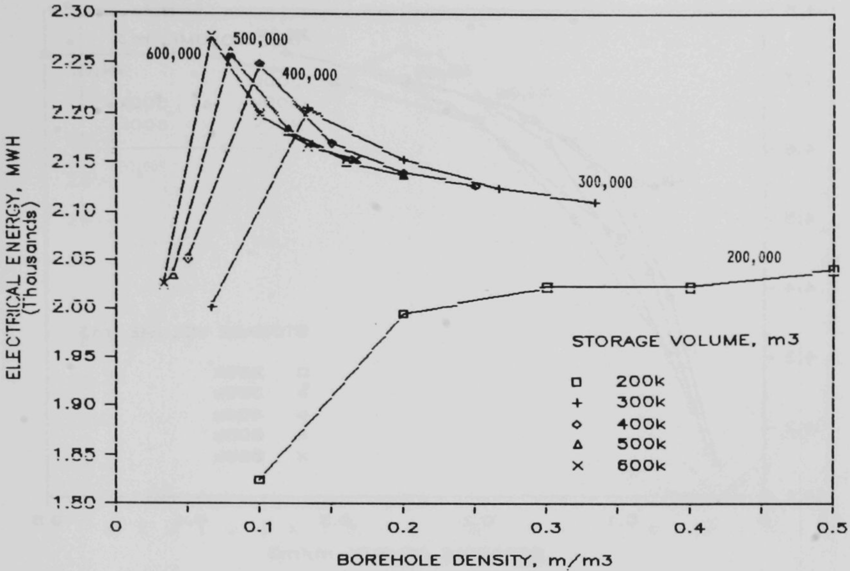


FIGURE 14 Electrical Energy Consumed by Heat Pump (Hartford, Conn.; low-temperature distribution; flat plate collectors, area = 15 x 10^3 m^2; all volumes)

System performance for the high-temperature-demand scenario was similar to the results presented above. However, the heat pump's COP was substantially reduced, resulting in a lower solar contribution.

4.3 SYSTEM SIMULATION OVER AN ANNUAL CYCLE

The results of the simulations presented in Secs. 4.1 and 4.2 are annual totals or averages derived over the simulated annual cycle, which was performed for each parameter set on a daily time step. In this section, a specific parameter set is selected for a detailed study of the system's operating characteristics over the simulated year. The system selected is well designed in terms of the relative component sizes and will be seen in Chapter 5 to be near an economic optimum. The parameters of the simulated system are as follows:

- Location: Hartford, Connecticut
- Collector type: flat plate collectors
- Collector area: 15,000 m^2

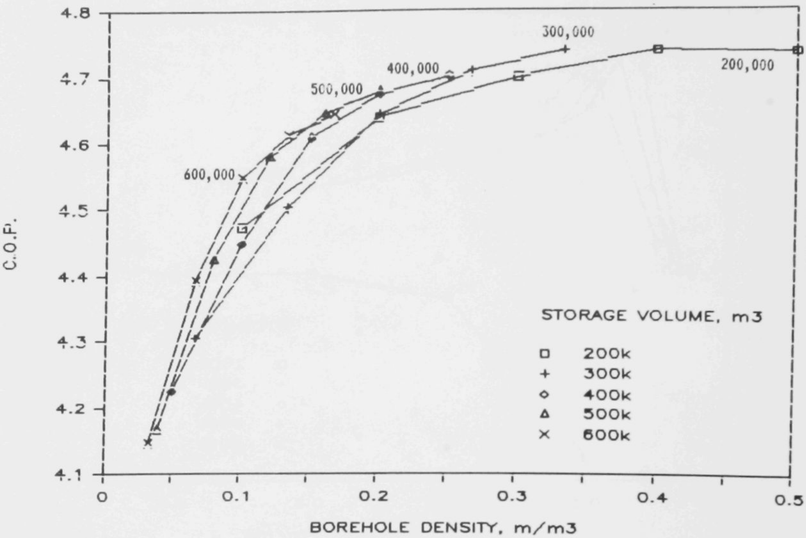


FIGURE 15 Annual Coefficient of Performance for Heat Pump (Hartford, Conn.; low-temperature distribution; flat plate collectors, area = 15 x 10^3 m^2; all volumes)

- Storage volume: 300,000 m^3

- Number of boreholes: 400 (depth = 100 m)

Results from the annual simulation are shown in Figs. 16 and 17. The average storage temperature exhibits a smooth cycle over the year, between a minimum of about 11°C and a maximum of 32°C. Figure 17 displays the system behavior in more detail. The energy flows are plotted in a cumulative manner over time, so the large daily fluctuations are not shown. The system load consists of only the small domestic hot-water (DHW) demand through September, at which time the winter space-heating demand starts and continues through March. The collector array is observed to be operating throughout the summer months with the energy going into storage, increasing the storage temperature so that it reaches a maximum in time for the winter heating season. Solar collection continues through the winter, but with much less success than during the summer; solar collection then increases with the approach of spring. Greater insolation is available in the spring, and the storage temperature is reduced to provide better collector efficiency.

The heat pump operates throughout the year (although operation is at a very low level during the periods requiring only DHW heating). The electrical consumption rises

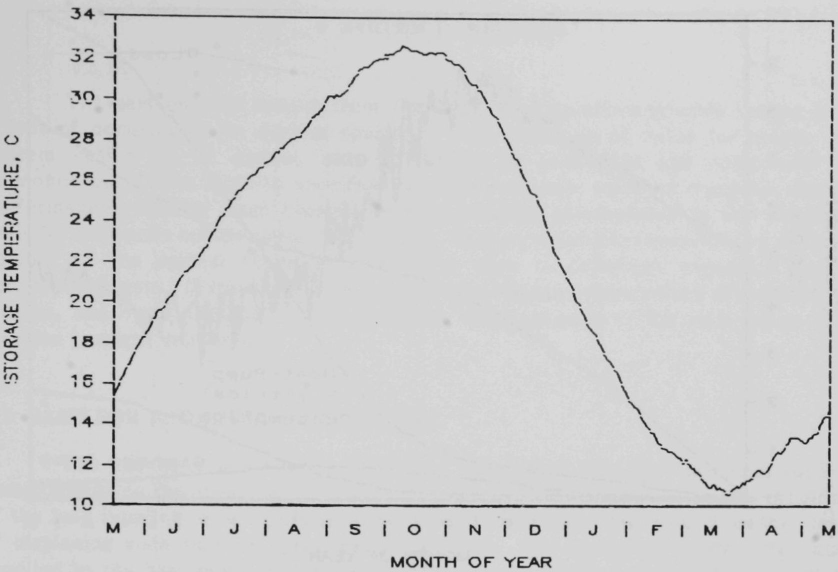


FIGURE 16 Simulated Annual Temperature Cycle for Storage System (Hartford, Conn.; flat plate collectors, area = 15 x 10^3 m^2; storage volume = 300 x 10^3 m^3; 400 100-m boreholes)

during the mid to late winter, when heating demands are high and storage temperatures are reduced. The COP curve shows substantial daily variation due to variations in daily demand. The general trend, however, is coupled to the storage temperature and the load demand. The DHW load is met during the summer with a good COP, which increases as the storage temperature (evaporator inlet temperature) increases. The COP falls rapidly as the large winter loads are met and the storage temperature falls. Overall, the heat pump can operate with COPs ranging from 3.5 to 8.5. Water-to-water heat pumps can operate with high COPs in seasonal-storage solar-energy systems because of the relatively high-temperature water source available. Ground-coupled heat pumps work from ambient ground temperatures of about 10°C; heat pumps operating from the air extract heat from the ambient winter air below 10°C.

The summary output file from the MINSUN simulation of this system is included in App. B.

4.4 GROUND-COUPLED HEAT-PUMP SYSTEMS

Space-heating systems using heat pumps to make use of the ambient ground temperature have been successfully implemented and share some characteristics in common with seasonal-storage systems. However, there are essential differences between these system types and their applicability.

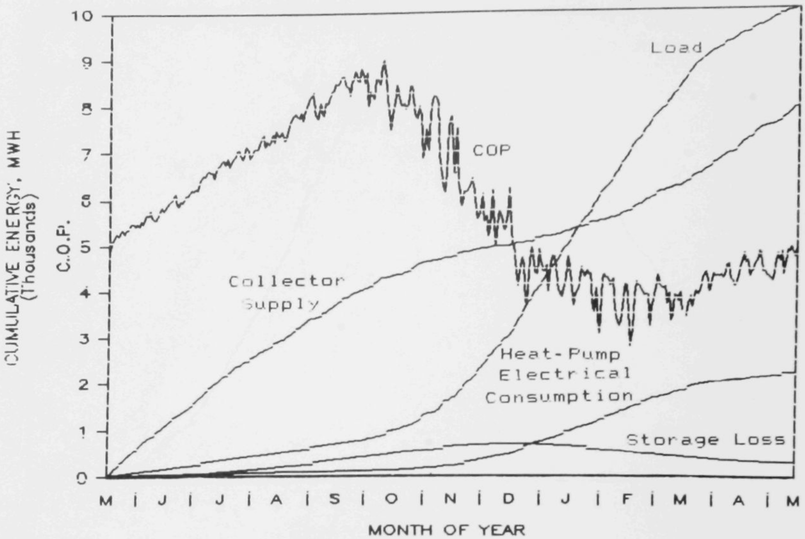


FIGURE 17 Simulated Annual Performance Cycle and System Energy Flow (Hartford, Conn.; flat plate collectors, area = 15 x 10^3 m^2; storage volume = 300 x 10^3 m^3; 400 100-m boreholes)

Ground-coupled heat pumps will operate successfully only when enough heat can be extracted **and** only when this amount of heat is completely replaced by natural heat transfer so that the ambient temperature characteristics are completely reinstated. Thus, wells must be spread out far enough apart to allow this heat and temperature regeneration during the nonheating periods; otherwise, ground-source temperatures will decrease over time, and system operation will deteriorate between successive heating seasons. On a large scale, these systems are not renewable, because they cannot maintain sufficiently high temperatures for operation without injecting a new source of heat. Solar energy provides good low-temperature heat in abundance over an annual cycle. Other heat sources, particularly waste heat, also can be stored economically if they are available at low cost.

5 SYSTEM ECONOMICS

The performance results from the MINSUN simulations provide insight into the effect of components on system operation that should be of value for proper design. System design is, of course, also influenced by economics and component costs. Economic conditions must be specified to place economic value on marginal changes in performance resulting from changes in system-design parameters. In this chapter, the basis for economic optimization is discussed. Various economic scenarios are defined and applied to the system thermal-performance data to construct expansion paths for optimum systems. (Expansion paths for optimum systems show values of collector area, volume, and other variables -- optimized in terms of cost -- for each value of solar fraction [energy] delivered.)

5.1 BASIS FOR ECONOMIC OPTIMIZATION

The economic optimum is defined as the system that provides solar (and heat-pump) energy to the consumer or distribution system at the lowest unit cost. Any portion of the load supplied by auxiliary or conventional fuels is not considered, so that the cost of displacing such fuels is specifically examined. The electrical energy that must be supplied to the heat pump is considered (both its contribution to the load and its cost); this energy is necessary in order to make use of low-temperature solar heat and is subject to different price structures than the displaced fuel. The economic optimization is based on the system energy cost (SEC), which is defined as the annualized capital and heat-pump operational cost divided by the solar output from storage and heat-pump input energy. Figure 18 shows the equations used to determine system cost and derive the system energy cost. These equations are the same as those used in the MINSUN economic analysis, except for a simplification used in the storage-cost equation.

5.2 ECONOMIC SCENARIOS

Due to the lack of experience in the United States with solar seasonal-storage technology, a great deal of uncertainty exists regarding cost of components and engineering and construction tasks. Such economic factors as discount rate, future electrical rates, and depreciation allowances and tax liability also are uncertain. The future of the federal energy tax credits after expiration in December 1985 is unknown. Other state and federal incentives may be available under specific circumstances, especially for the construction of a first system.

Several economic scenarios have been defined to cover a range of possible situations. The parameters and financial conditions that define these scenarios, given in Table 2 and in Fig. 19, are chosen to represent the following circumstances:

1	Base-Case Scenario:	Best available present cost and economic conditions
2	Low-Cost Scenario:	Lowest cost conditions likely

Collectors

COLCOS = AREA(Cost/Area) + (Pipe Length)(Cost/Length)

Storage

STOCOS = (Borehole Depth)(No. of Boreholes)(Cost/m)
+ Fixed Cost

Heat Pump

Let AAH = $[(\text{Maximum Condenser Power})/0.6]^{-0.3}$

EVAP = (Evaporator Capacity)(Evaporator Unit Cost) AAH x 10^3
COND = (Condenser Capacity)(Condenser Unit Cost) AAH x 10^3
MOTOR = (Maximum Electric Power)(Motor Unit Cost) AAH x 10^6

HPCOS = EVAP + COND + MOTOR

Total Capital Cost

COSCAP = COLCOS + STOCOS + HPCOS

Heat-Pump Operation (first year)

HPOPER = (Electrical Consumption)(Electrical Rate)

System Energy Cost

SEC = [(COSCAP)(AKAP) + (HPOPER)(AFUEL)] / (TSTRG + QPELH)

where:

TSTRG = Collector and Storage Solar Supply
QPELH = Heat-Pump Electrical Consumption
AKAP = Capital Annualization Factor Based on Real Discount Rate
AFUEL = Fuel Annualization Factor Based on Real Discount Rate and Fuel Escalation Rate

FIGURE 18 Cost Equations and Derivation of System Energy Cost

TABLE 2 Economic Scenarios[a]

Component Cost or Economic Factor	Base Case (1)	Low-Cost (2)	High Cost (3)	With Depreciation (4)[b]	With Federal Tax Credits (5)[b]
Collector ($\$/m^2$)					
Flat Plate	250	200	325	250	250
Unglazed	140	100	175	140	140
Piping	250	200	300	250	250
Storage					
Borehole ($/m)	20	15	35	20	20
Fixed Cost ($\$10^3$)	35	20	50	35	35
Heat Pump					
Evaporator ($/W·K)	0.2	0.15	0.3	0.2	0.2
Condenser ($/W·K)	0.2	0.15	0.3	0.2	0.2
Elec Motor ($/kW)	0.2	0.15	0.3	0.2	0.2
Heat-Pump Operating Cost					
Electrical Rate ($/kWh)	0.06	0.03	0.09	0.06	0.06
Escalation (%)	1.5	0	3.0	1.5	1.5
(AFUEL)	(1.13)	(1.00)	(1.25)	(1.13)	(1.13)
Discount Rate (%)	5	2	8	5	5
(AKAP)	(0.076)	(0.060)	(0.094)	(0.076)	(0.076)

[a]A 20-year system lifetime is assumed in all scenarios.

[b]Values in this column are the same as those for the base case but are treated differently; see Fig. 19 and explanation in text.

3 High-Cost Scenario: Highest cost conditions likely

4 Scenario with Depreciation Allowance: Accounts for impact on base-case conditions of depreciation allowances, with sufficient tax liability

5 Scenario with Federal Tax Credits: Accounts for impact on base-case conditions of depreciation and federal investment and energy tax credits, with sufficient tax liability

Economic Scenarios 4 and 5:

Depreciation Using Five-Year Accelerated Schedule:

Year	1	2	3	4	5
Percent Depreciated	15	22	21	21	21

Business Tax Rate = 46%

Economic Scenario 5:

Investment Tax Credit = 10%
Energy Tax Credit = 15%

Basis for Depreciation is Capital Cost after Tax Credits.

System Energy Cost is as Defined in Fig. 18; However, for Economic Scenarios 4 and 5:

$$\text{COSCAP} = x - 0.46\left[\frac{0.15\ x}{(1+r)} + \frac{0.22\ x}{(1+r)^2} + \frac{0.21\ x}{(1+r)^3} + \frac{0.21\ x}{(1+r)^4} + \frac{0.21\ x}{(1+r)^5}\right]$$

where r = Real Discount Rate and COSCAP is as Defined in Fig. 18,
for Economic Scenario 4: x = COSCAP
for Economic Scenario 5: x = [COSCAP - (0.10)(COSCAP) - (0.15)(COSCAP)]
= (0.75)(COSCAP)

FIGURE 19 Financial Calculations for Economic Scenarios 4 and 5

Economic scenarios 4 and 5 entail a bit more complexity than the others, but they still represent a great simplification of the actual financial analysis likely to be involved in the implementation of such a project. The present federal tax law is still vague in some areas and remains untested by the application of a CSHPSS system. The Investment Tax Credit (ITC) of 10% excludes energy property used exclusively for space heating or cooling (though this usually refers to "structural components" of buildings, as conventional heating, ventilation, and air-conditioning equipment is defined). This exclusion is also valid for the accelerated five-year depreciation allowance, instead of the normal 15-year schedule. However, the Internal Revenue Service (IRS) Code indicates that the ITC and five-year depreciation can be taken for energy systems that provide hot water. There is much ambiguity of interpretation concerning systems located away from the building and not owned by the owner of the building.[11]

The Business Energy Tax Credit (ETC) expires at the end of 1985, and the prospects for extension are unknown. The ETC, which provides a 15% tax credit, would be applicable to CSHPSS systems.

As indicated in Fig. 19, the economic scenarios used in this analysis assume that both credits and the accelerated depreciation can be applied to the capital cost of the system. The scenarios assume the owner is subject to a business tax rate of 46% and has sufficient tax liability to take immediate advantage of the tax reductions, although the tax credits can be carried back or forward a number of years.

5.3 RESULTS OF ECONOMIC ANALYSIS

5.3.1 Base-Case Results

The base-case economic scenario is applied to the base-case system (Hartford, Conn.; 10,000 MWh; low-temperature load). For each combination of parameters, values for the solar fraction and SEC are produced. The points are plotted in Figs. 20 and 21 for both collector types. The expansion path is the envelope of these points; it defines the minimum SEC for each solar fraction.

For both collector types, the SEC increases sharply beyond a solar fraction of about 78%. At this solar fraction, the energy cost of the optimum flat plate system is about $52/MWh, while that of the optimum unglazed collector system is about $44/MWh.

The symbols in Figs. 20 and 21 represent the various collector areas; as the expansion path is followed to higher solar fractions, the optimum collector area increases. A characteristic pattern of the set of points for a given collector area is illustrated by the drawn lines. Storage volume has no direct effect on cost but does influence performance. As was seen in the performance curves (Figs. 10 and 11), volume has little effect at large areas. The effect of volume is to move the point in a manner indicated by the downward-slanting arrow in Fig. 20; the SEC is affected only by the corresponding change in performance. The number of boreholes directly affects both cost and performance; the effect of increasing the number of boreholes is to increase the solar fraction. Beyond a certain number of boreholes, this performance increase does not cover the additional cost of drilling the boreholes.

5.3.2 Results under Other Economic Scenarios

The expansion paths for the base-case system (Hartford, Conn.; low-temperature distribution) have been derived for the remaining economic scenarios. These results are plotted in Figs. 22 and 23 for both collector types, where the symbols denote the various scenarios. Generally, the high-cost scenario increases the base-case SEC by about 70%, while the low-cost scenario reduces the SEC by about 45%. The financing scenarios (4 and 5) also provide significant energy-cost reductions, which substantiate their importance in the economic analysis of these systems.

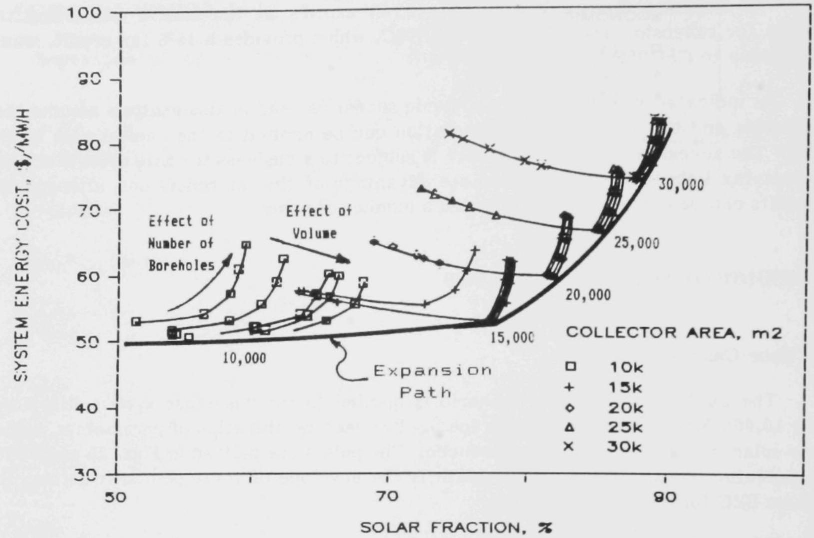


FIGURE 20 Base-Case Economic Results and Expansion Path Using Flat Plate Collectors (Hartford, Conn.; collector areas given by symbol key)

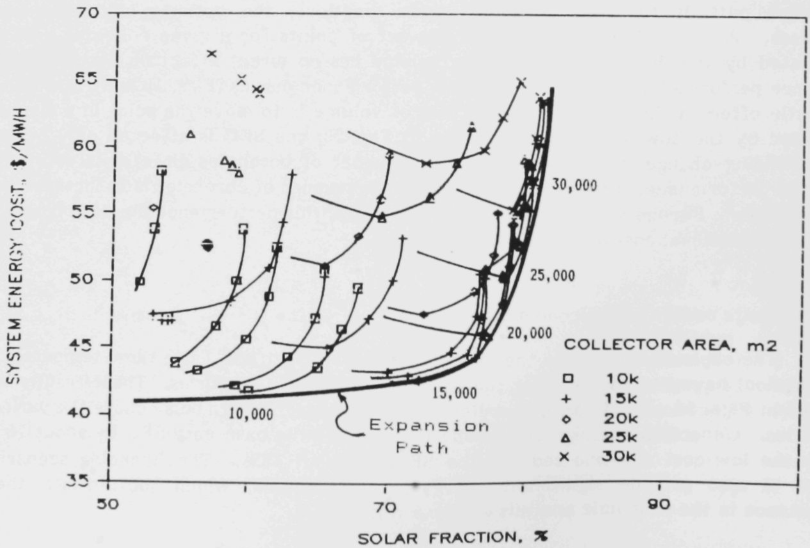


FIGURE 21 Base-Case Economic Results and Expansion Path Using Unglazed Collectors (Hartford, Conn.; collector areas given by symbol key)

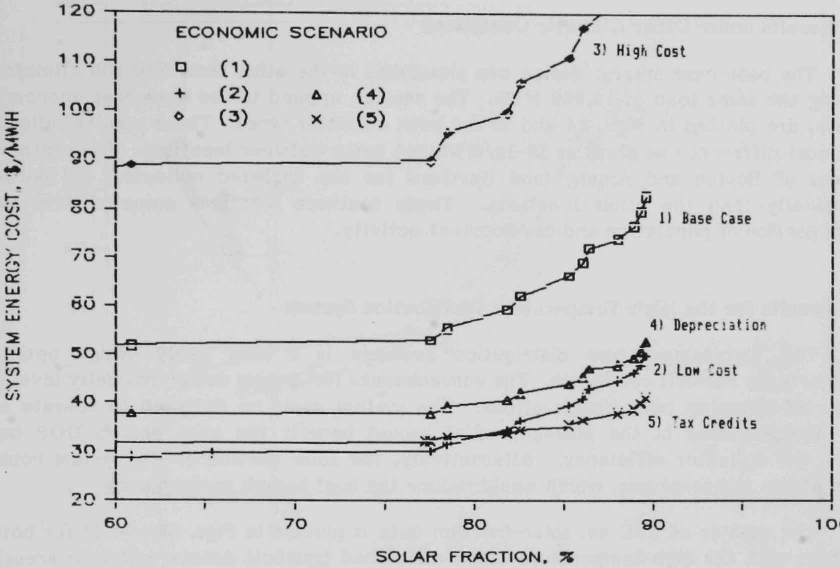


FIGURE 22 Expansion Paths for All Economic Scenarios with Base-Case System Using Flat Plate Collectors (Hartford, Conn.; low-temperature distribution)

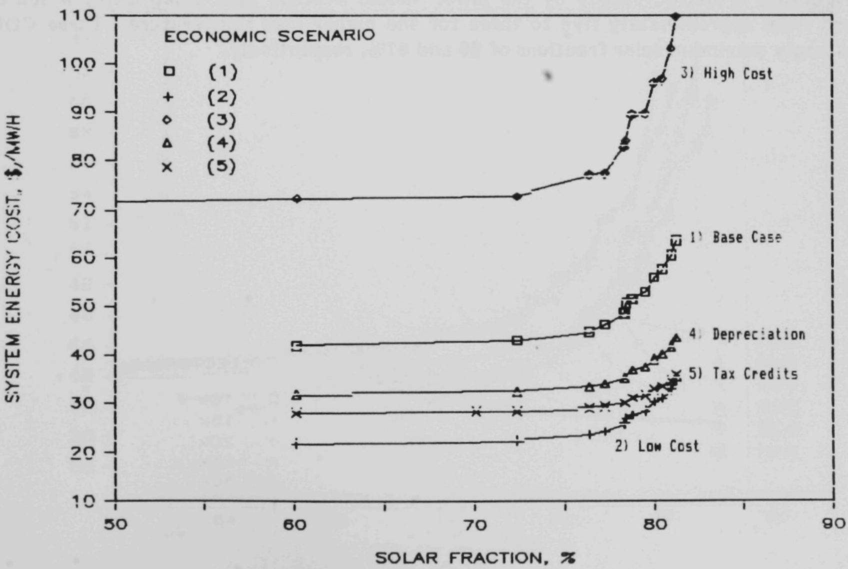


FIGURE 23 Expansion Paths for All Economic Scenarios with Base-Case System Using Unglazed Collectors (Hartford, Conn.; low-temperature distribution)

5.3.3 Results under Other Climatic Conditions

The base-case system design was simulated in the other New England climates, assuming the same load of 10,000 MWh. The results, applied to the base-case economic scenario, are plotted in Figs. 24 and 25 for both collector types. These results indicate that a cost difference as great as $5-10/MWh can occur between locations. The southern locations of Boston and Albany (and Hartford for the unglazed collector) did better economically than the other locations. These southern locations coincide with the greater portion of population and development activity.

5.3.4 Results for the High-Temperature Distribution System

The high-temperature distribution scenario is a very likely design option, particularly for retrofit conditions. The consequences for system design basically involve a trade-off between two considerations. The system could be designed to operate at higher temperatures in the storage, which would benefit the heat pump's COP but degrade the collector efficiency. Alternatively, the solar portion of the system could remain at low temperatures, which would reduce the heat pump's performance.

The scatter of SEC vs. solar-fraction data is plotted in Figs. 26 and 27 for both collectors with the high-temperature distribution load (symbols denote collector areas). Figure 28 compares the expansion paths for both collectors and both distribution temperatures under the base-case economic scenario. The results show a significant increase in energy cost at high temperatures and a reduction in the feasible solar fraction; the effect is more pronounced for the unglazed collectors. The reduction in solar fraction is caused mainly by the lower annual average heat-pump COP, which is reduced from approximately five to three for the higher load temperature. These COP values imply maximum solar fractions of 80 and 67%, respectively.

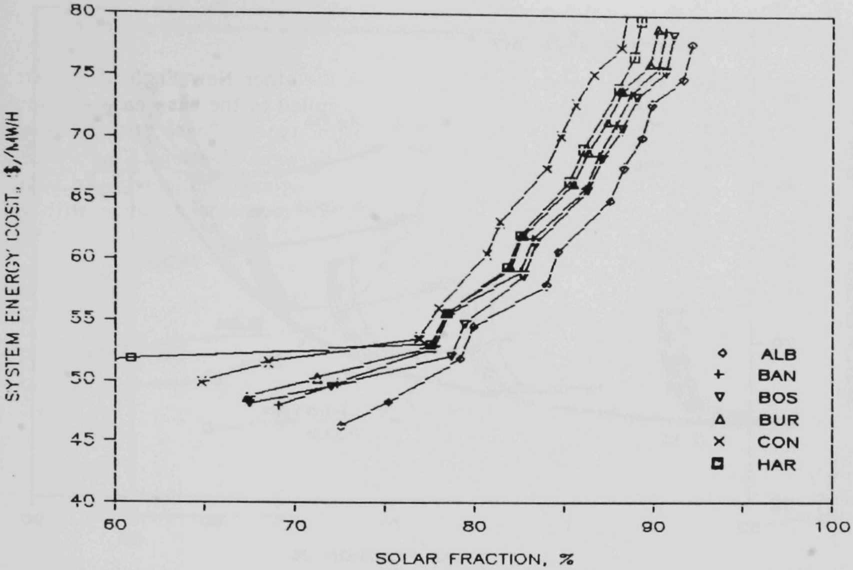


FIGURE 24 Base-Case Expansion Paths for All Climatic Regions Using Flat Plate Collectors

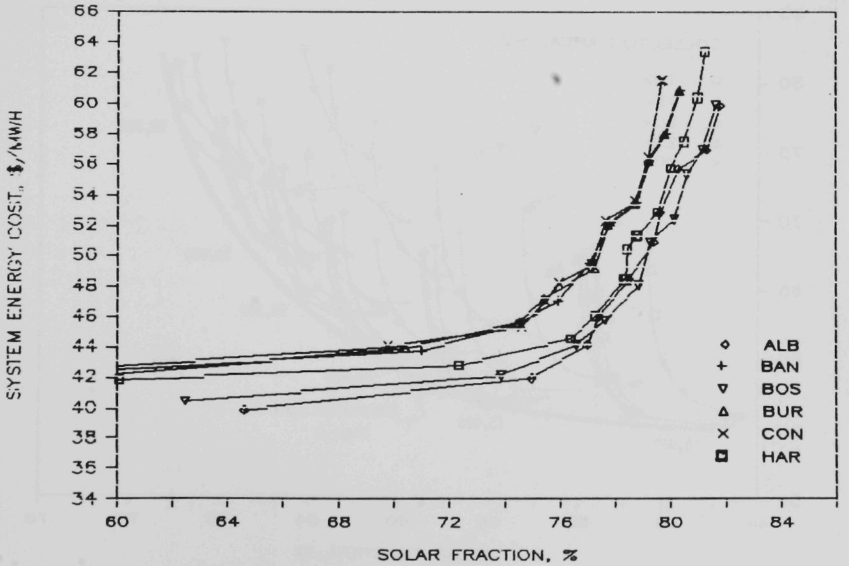


FIGURE 25 Base-Case Expansion Paths for All Climatic Regions Using Unglazed Collectors

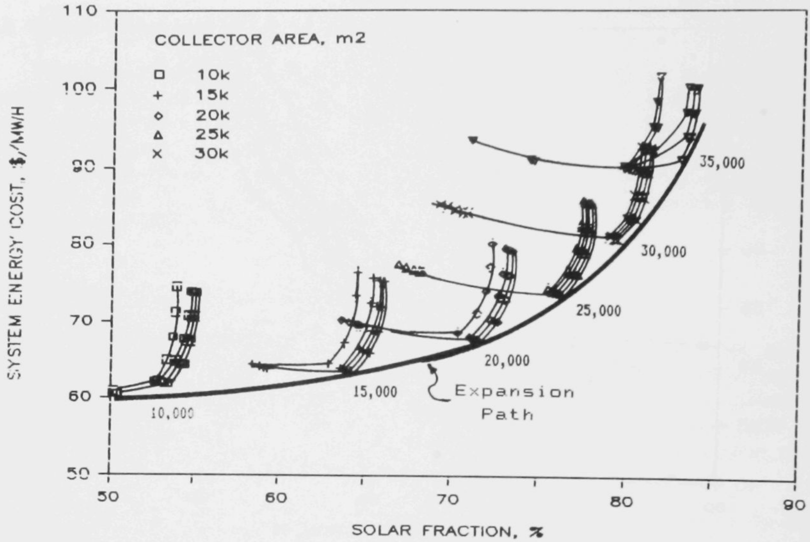


FIGURE 26 Economic Results and Expansion Path for High-Temperature Distribution System Using Flat Plate Collectors (Hartford, Conn.)

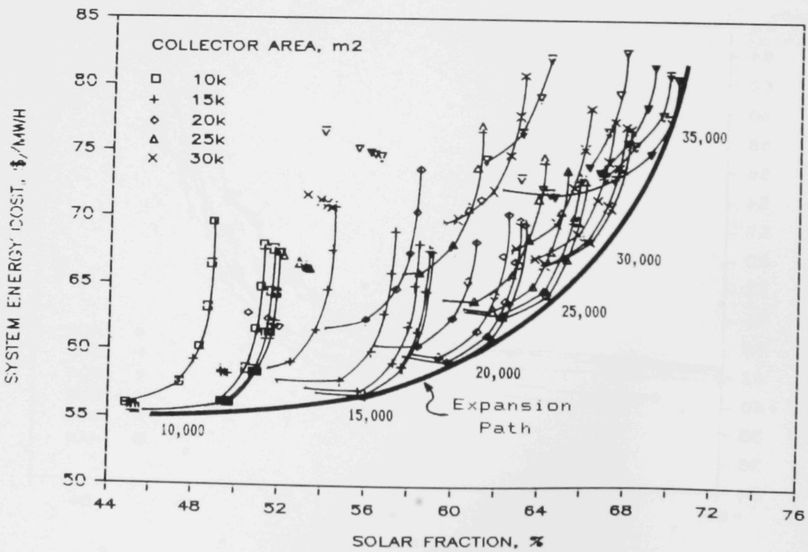


FIGURE 27 Economic Results and Expansion Path for High-Temperature Distribution System Using Unglazed Collectors (Hartford, Conn.)

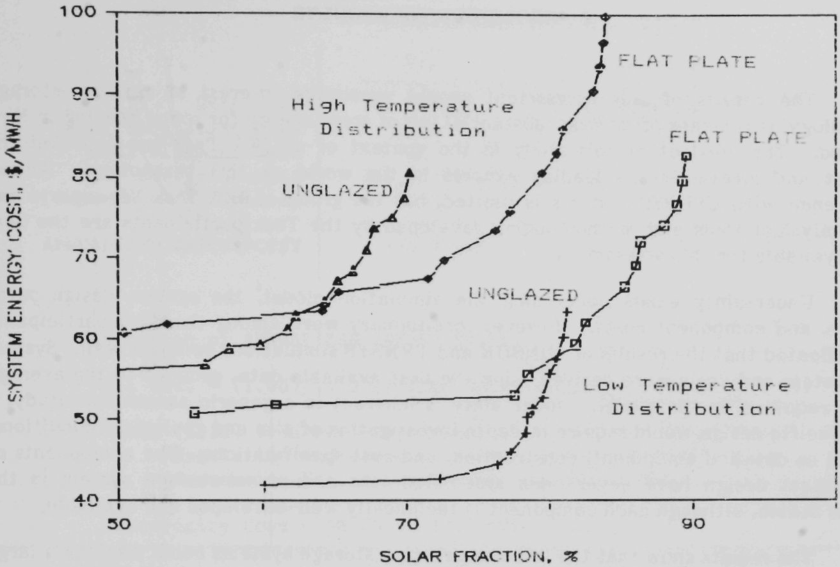


FIGURE 28 Expansion Paths for Low- and High-Temperature Distribution Systems Using Both Flat Plate and Unglazed Collectors (Hartford, Conn.)

6 DISCUSSION OF RESULTS

The results of this assessment should encourage interest in seasonal-storage technology as a means of making substantial use of solar energy for space heating in New England. The conduct of this study in the context of an IEA Task has provided the support and advice of the leading experts in the world on this technology. Actual experience with CSHPSS systems is limited, but the group of IEA Task VII experts and the analytical tools and methodologies developed by the Task participants are the best ones available for this assessment.

Uncertainty exists concerning the simulation model, the system design parameters, and component costs. However, preliminary work among the Task participants has indicated that the results of MINSUN and TRNSYS simulations compare well. System parameters and costs were derived using the best available data, reduced to the average terms required by the model. Uncertainty is inherent in a generic assessment study; a site-specific design would require in-depth investigation of site and geological conditions, as well as detailed equipment, construction, and cost specifications. The components of the system design have never been assembled into a seasonal-storage system in the United States, although each component is technically well-developed and available.

The results show that the low-temperature storage systems could displace a large portion of the load with solar energy. Unglazed collector systems would provide energy at a lower cost but could not provide as large a solar fraction as could the flat plate systems. The distribution temperature is an important design condition and should be kept as low as possible.

This assessment did not consider the cost or performance of the distribution system, because the cost of this subsystem is particularly site-specific and dependent on load density, site of the storage facility, stage of load development, and distribution temperature. Heat loss from the distribution system can be kept very low. The range of cost for the distribution system is expected to increase the energy cost by about 5-35%. The best site would involve a new construction and a dense load, with the solar heating system placed nearby.

It is instructive to determine the cost of conventional heating on a basis that renders it comparable with the results of this study. Two scenarios are considered over the 20-year system lifetime -- a heating system based on oil and an electrical-resistance heating system. The parameters assumed and the annualized delivered energy costs determined are given in Fig. 29.

In comparison with conventional heating costs, the results of this assessment indicate that solar energy from seasonal-storage systems can cost-effectively displace conventional fuels for space heating and that actual system energy cost can be reduced even further with financing opportunities provided by federal legislation. These economic results are exclusive of other benefits, including price stability, lessened environmental impact, energy independence, and an improved local economy.

Conventional Heating System

	Oil	Electricity
Unit Cost	$1.00/gal	$0.05/kWh
Real Escalation Rate	1.5%	1.5%
Real Discount Rate	5%	5%
Energy Content	138,500 Btu/gal	not applicable
Conversion Efficiency	0.70	1.0
ANNUALIZED ENERGY COST	$39.7/MWh	$56.5/MWh

Derivation of ANNUALIZED ENERGY COST:

Oil Cost = $(1.00)(1.13)(1/138{,}500)(1/0.70)(3.412 \times 10^6) = 39.7$

where (1.13) is a Fuel-Cost Escalation Factor Derived from Escalation and Discount Rate, and (3.412×10^6) is a Conversion Factor for Converting Btu to MWh.

Electricity Cost = $(0.05)(1.13)(1000) = 56.5$

FIGURE 29 Calculation of Annual Cost for Conventional Heating Scenarios

7 CONCLUSIONS AND RECOMMENDATIONS

The results of this assessment have important implications in terms of the opportunity for substantial use of solar energy for space heating in New England. The major conclusions of this study and recommendations supported by the study and other IEA Task work are summarized below.

7.1 CONCLUSIONS

The results of this assessment are based on the best available system component-performance and cost data and make use of the best available in analytical tools and methodologies. Results show the following:

- Solar energy stored through ducts in bedrock on a seasonal basis can compete economically with conventional heating methods and will effectively displace (with a heat pump) almost the entire load.

- The economic scenarios and financing arrangements under which these systems are implemented are very important in terms of the overall economics of the project.

- No technical barriers to the implementation of CSHPSS systems exist, although in the United States the required components have never been designed and operated together in the manner or on the scale contemplated here.

- Although the concept has not been included directly in this study, it appears likely that future CSHPSS systems will be designed to include a smaller, short-term storage tank.* This tank would allow a great deal of operational flexibility; it could be used to meet peaks in demand, to allow a longer period of time for heat transfer into and out of the long-term storage, to make use of off-peak electric rates for heat-pump operation, and to facilitate direct collector-to-load operation. The influence on performance of the small diurnal tank is essentially accounted for by the one-day time step of the simulator.

- The major barrier to the use of seasonal-storage technology is not technical, but institutional. These systems must be built on a fairly large scale, and they require a great deal more planning and design than do conventional heating schemes. The uncertainties inherent in any new technology make initial implementation more risky than

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*The existing MINSUN code cannot simulate explicitly operations using the smaller tank, but the code effectively simulates its use by employing a daily time step.

the private sector is accustomed to accept. Furthermore, large-scale developers, energy planners, and financial institutions often lack the knowledge of this technology needed for its implementation.

7.2 RECOMMENDATIONS

- Energy policy in the New England region should be concerned with reducing consumption of conventional fuels for low-temperature heating (or cooling) loads and should actively support solar (and ice) seasonal-storage technology as a viable and economically competitive option. Seasonal storage is the only significant solar technology to displace large space-heating loads with very high solar fractions.

- The general results of the IEA Task VII, Subtask II(b), work support the economic attractiveness of seasonal-storage systems, based on the other storage technologies (specifically, aquifers and constructed water pits). The New England climate is also quite suitable for seasonal storage of winter ice for cooling of residential and commercial spaces in the summer. Ice-storage technology shares many similarities with that used in the heating systems under consideration and is also technically feasible and (to some extent) demonstrated. Winter cold can be stored by the formation and storage of ice, or it can be used in sensible-heat storage in an aquifer or a duct system. Combining the heating and cooling systems may offer substantial benefits in economies of scale and dual usage of some components. A heat pump can be used effectively to exchange heat at the two temperature levels.

- A demonstration system is needed to provide technical design and operational experience and to educate the public. Such a project should be privately financed as much as possible, with public support to reduce the investors' financial risk and carry the differential costs associated with first-time construction and a desirable level of scientific monitoring and evaluation.

- Phase III of IEA Task VII, which is to commence in 1985-86, calls for international expert support and data exchange among national demonstration systems. Each participating country must contribute by means of its own demonstration project. The United States has indicated its initial support for participation in Phase III and pursuit of a demonstration system. The opportunity to proceed in a demonstration project within the structure of the IEA Task would be very valuable in terms of expert technical support, continued data exchange on other national projects, and public exposure.

REFERENCES

1. Bankston, C.A., *Central Solar Heating Plants Using Seasonal Storage: Basic Performance, Cost, and Operation of Solar Collectors for Heating Plants with Seasonal Storage*, Argonne National Laboratory, Report ANL/ES-139 (May 1983).

2. Bankston, C.A., *Evaluation of Concepts for Central Solar Heating Plants with Seasonal Storage*, unpublished draft prepared for International Energy Agency, Solar Heating and Cooling Program, Task VII, Subtask II(b) (Nov. 1984) [available from C.A. Bankston, Inc., 2861 Arizona Terrace, N.W., Washington, D.C. 20016].

3. Hadorn, J.C., *Central Solar Heating Plants Using Seasonal Storage: Evaluation of Systems Concepts Based on Duct Storage*, working document prepared for International Energy Agency, Solar Heating and Cooling Program, Task VII, Subtask II(b) (June 1984) [available from J.C. Hadorn, Sorane S.A., Route du Châteland JZ, 1018 Lausanne, Switzerland].

4. Chant, V.G., and D.S. Breger, *Central Solar Heating Plants Using Seasonal Storage: Evaluation of Systems Concepts Based on Heat Storage in Aquifers*, working document prepared for International Energy Agency, Solar Heating and Cooling Program, Task VII, Subtask II(b) (Oct. 1984) [available from James F. Hickling Management Consultants, Ltd., 350 Sparks St. (suite 605), Ottawa, Ontario, Canada K1R 7S8].

5. Chuard, P., and J.C. Hadorn, *Central Solar Heating Plants Using Seasonal Storage: Heat Storage Systems: Concepts, Engineering Data and Compilation of Projects*, International Energy Agency, Solar Heating and Cooling Program, Task VII, Subtask I(c) (June 1983) [available from Eidgenossische Drucksachen und Material Zentrale, Bern, Switzerland].

6. Frimpter, M., United States Geological Survey, Boston, Mass., personal communication (Sept. 19, 1984).

7. Sherman, R., and C. Sweet, Metcalf and Eddy, Inc., Boston, Mass., personal communication (Aug. 22, 1984).

8. Yule, M., State Office of Communities and Development, Boston, Mass., personal communication (Aug. 21, 1984).

9. *Central Solar Heating Plants Using Seasonal Storage: The MINSUN Simulation and Optimization Program: Application and User's Guide*, V.G. Chant and R. Hakansson, eds., prepared by National Research Council, Canada, for International Energy Agency, Solar Heating and Cooling Program, Task VII, Subtask I(a) (Dec. 1983) [available as CENSOL2 from Technical Information Office, Solar Energy Program, National Research Council, Ottawa, Ontario, Canada K1A OR6].

10. The following solar collector manufacturers were contacted by phone for information regarding flat plate and unglazed collector performance and cost: Bio-Energy Systems Co., Ellenville, N.Y.; FAFCO, Inc., Menlo Park, Calif.; Sunglo Solar, Ltd., Concord, Ontario, Canada.

11. Brenner, C.W., *Third Party Financing - A Primer for the Baffled Energy Professional*, Commonwealth Energy Group, Ltd., Winchester, Mass. (1983).

APPENDIX A: DUCT STORAGE IN ROCK*

*Excerpted from Ref. 5.

3.6. Rock storage concepts (by P.O. Karlsson, Sweden)

3.6.1. Technical description

A multiple well system in rock may be used for seasonal storage of thermal energy. The system function is based on the heat conductivity and storage capacity properties of the rock.

The heat is transferred to or from the rock by means of water circulated through a large number of boreholes or wells. The boreholes normally do not need casing.

The heat storage capacity of rock material such as gneiss and granite is about half the heat capacity of water. Hence, a multiple well heat storage system must have a volume twice as large as a water cavern with similar storage capacity /51/.

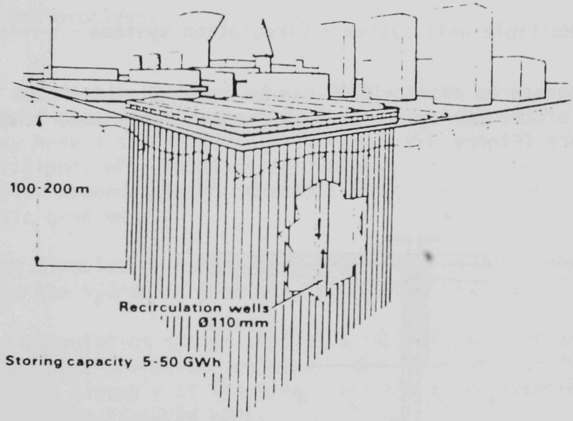


Figure 10: Multiple-well heat storage - Principal sketch

The heat carrying fluid, normally water, can be circulated through the wells in open or closed circulation systems (see Figure 11).

In a closed circuit system, the fluid is circulated through U-shaped tubes inserted into the wells. Ground water transfers the heat to and from the tube and the rock. The circulation fluid has no direct contact with the rock. Therefore, even if the storage system is constructed in a fissured rock, no loss of water will occur, nor will there be any problem of chemical precipitation in tubes or heat exchangers.

In an open circuit system, the fluid is conducted through a tube to the bottom of the well where it is released in direct contact with the rock. To limit heat and water losses, a multiple well heat storage system utilizing an open circulating system requires rock with a relatively low permeability.

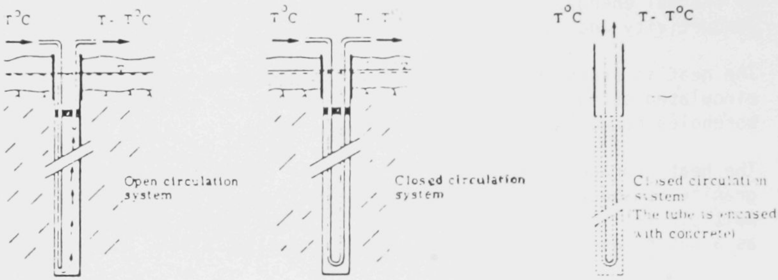


Figure 11: Multiple-well system - Circulation systems

Storage temperatures above +100°C can be used, provided the active part of the storage is at a sufficient depth under the ground surface (Figure 12).

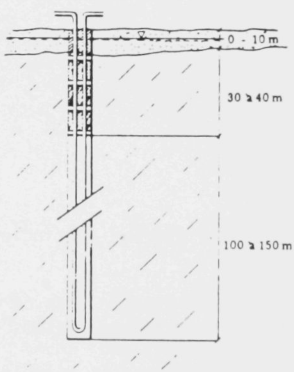


Figure 12: Closed circulation system
Storage temperature: 120-140°C

3.6.2. Applicability

The multiple well heat storage is applicable in many kinds of hard rock as granite and gneiss and can be easily located in places with a relatively thin covering soil layer. It can be constructed at comparatively low costs and with well-known technology /49/.

The storage system can be used for temperatures from 10°C up to above 100°C in some cases. This allows storage from different kinds of heat sources as waste heat and solar heat. The storage concept is primarily applicable for seasonal storage.

In some areas with a very thick soil layer above the bedrock, or in dense utilized areas, it would be possible to construct a tunnel system in the bedrock and drill the boreholes downwards, and create a multiple well heat storage system under the tunnels.

3.6.3. Design and problems

Before any design, the hydrogeological conditions must be determined clearfully. The natural or superimposed ground water flow may have a significant influence on the thermal behaviour and efficiency of a multiple well heat storage system. The ground water flow depends on the permeability of the rock and the hydraulic gradient.

A closed circulation system can be used even in fissured rock provided the hydraulic gradient is sufficiently low.

An open circulation system implies a superimposed hydraulic gradient because of the operation pressure. Hence, an open circulation system must always - if grouting, etc. are to be avoided - be placed in non or less fissured rock.

Different strategies can be applied for the charging and discharging operations. all parts of the storage volume can be charged or discharged at the same time, i.e. all the wells are throughflowed by similar flow at the same temperature level. A more efficient strategy implies that the storage is charged beginning in the centre and then outwards in a radial direction. Discharging will then be done by a reversed operation.

Different temperature zones can be formed within the storage by connecting the boreholes by groups (Figure 13).

To allow multiple-well designs to provide higher power outputs, the rock storage can be combined with a "buffer-tank", for instance water-filled tunnels used for daily storage /50/.

3.6.4. Experience

A pilot test involving storage at low temperature (35°C) has been carried out at Sigtuna, Sweden. The system is a closed circulation system. The experiences during the years of operation have shown a good coincidence with theoretical calculations. Initially, some practical and technical problems occurred, which, however, were rapidly solved. The tests will continue.

A multiple well storage downscaled 1:4 has been constructed in Luleå in the north of Sweden. The storage has 19 wells 19 m deep, with an open circulation system. Five years of seasonal heat injection and extraction have been simulated. The evaluation of continuous temperature measurements, within as well as outside the storage, shows that the storage operates in good accordance to the mathematical models worked out by Johan Claesson et al., University of Lund.

Another larger multiple well system comprising 120 wells, 65 m deep, has been built in Luleå. Operations will start during the summer 1983, and will be evaluated by the University of Luleå during a period of three years /47,48/.

Full-scale field tests, mainly concerning heat transfer from fluid to the surrounding rock, are currently carried out at Älvkarleby Hydraulica Laboratory and at Studsvik.

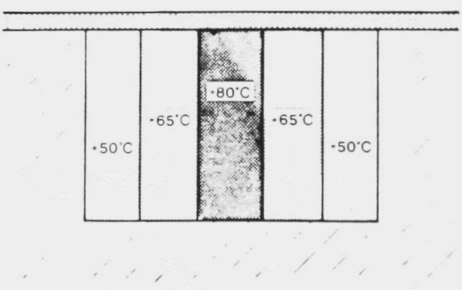


Figure 13: Temperature zones in a cylindrical multiple-well storage - Principal sketch

APPENDIX B: OUTPUT DATA FROM MINSUN SIMULATIONS

APPENDIX B: OUTPUT DATA FROM MINSUN SIMULATIONS

This appendix presents the summary output file for a MINSUN simulation (annual simulation of the system discussed in Sec. 4.3), followed by tables displaying the output results for MINSUN simulation runs under the following conditions:

- Table B.1 -- Flat plate collectors, low-temperature distribution
- Table B.2 -- Unglazed collectors, low-temperature distribution
- Table B.3 -- Flat plate collectors, high-temperature distribution
- Table B.4 -- Unglazed collectors, high-temperature distribution

MINSUN Summary Output File - Partial
(cost output adjusted to assessment values)

S T A R T   O F   C A L C U L A T I O N

C A P A C I T Y   R E Q U I R E M E N T S

MAXIMUM AUXILIARY HEATER POWER (HOUSE) (MW)	3.149
MAXIMUM AUXILIARY HEATER POWER (TAP WATER) (MW)	0.000
MAXIMUM CONDENSER POWER (HOUSE HEATING) (MW)	3.992
MAXIMUM CONDENSER POWER (TAP WATER) (MW)	0.000

C O S T   F U N C T I O N   F A C T O R S

TOTAL CAPITAL COST OF HEATING SYSTEM	5.294E+06	US$
CAPITAL COST ANNUALISATION FACTOR	7.642E-02	
FIRST YEAR OPERATING COSTS FOR SYSTEM	1.146E+05	US$
OPERATING COST ANNUALISATION FACTOR	1.18	
AVERAGE YEARLY COSTS (CAPITAL + OPERATION)	5.398E+05	US$

C A P I T A L   C O S T   S U M M A R Y

ALL COSTS IN THOUSANDS OF US$

COST OF SOLAR COLLECTORS	3750.0
COST OF STORE EXCAVATIONS	835.0
COST OF CONCRETE	0.0
COST OF STORE INSULATION	0.0
COST OF HOUSE HEATING HEAT PUMP CONDENSER	34.0
COST OF TAP WATER HEAT PUMP CONDENSER	0.0
COST OF HOUSE HEATING HEAT PUMP EVAPORATOR	56.6
COST OF TAP WATER HEAT PUMP EVAPORATOR	0.0
COST OF HOUSE HEATING HEAT PUMP MOTOR	153.8
COST OF TAP WATER HEAT PUMP MOTOR	0.0
COST OF GROUND FOR STORE	0.0
INSTALLED COST FOR AUXILIARY HEATER (HOUSE)	314.9
INSTALLED COST OF AUXILIARY HEATER (TAP WATER)	0.0
COST OF COLLECTOR ARRAY PIPEWORK (CENTRAL)	150.0
COST OF COLLECTOR ARRAY PIPEWORK (HOUSE MOUNTED)	0.0
COST OF HOUSE HEATING DISTRIBUTION NETWORK	0.0
COST OF TAP WATER DISTRIBUTION NETWORK	0.0

HEAT FLOW SUMMARY

COLLECTOR SUB-SYSTEM

COLLECTOR OUTPUT	7933.14 MWH	
CENTRAL COLLECTORS		
PIPE LOSS FORWARD	10.51 MWH	
PIPE LOSS RETURN	12.76 MWH	
COLLECTOR SUPPLY		7909.86 MWH

STORAGE SUB-SYSTEM

STORAGE LOSSES	304.51 MWH	
COLLECTOR SUPPLY MINUS STORAGE LOSSES		7605.35 MWH
STORED HEAT YEAR END MINUS YEAR BEGINNING	-106.51 MWH	
COLLECTOR AND STORAGE SUPPLY		7711.86 MWH

AUXILIARY

HEAT PUMP ELECTRIC ENERGY		
HOUSE HEAT	2217.27 MWH	
TAP WATER	0.00 MWH	
AUXILIARY HEATER		
HOUSE HEAT	75.57 MWH	
TAP WATER	0.00 MWH	
TOTAL SUPPLY		10004.70 MWH

LOAD

DISTRIBUTION LOSS FORWARD		
HOUSE HEAT	0.00 MWH	
TAP WATER	0.00 MWH	
DISTRIBUTION LOSS RETURN		
HOUSE HEAT	0.00 MWH	
TAP WATER	0.00 MWH	
HOUSE LOAD	10004.70 MWH	
TOTAL LOAD		10004.70 MWH

RATIOS

COLLECTOR SUPPLY/TOTAL LOAD	79.06 PERCENT
COLLECTOR SUPPLY MINUS STORAGE LOSSES/TOTAL LOAD	76.02 PERCENT
COLLECTOR AND STORAGE SUPPLY/TOTAL LOAD	77.08 PERCENT

T E M P E R A T U R E S   O F   S T O R A G E

START   15.3 15.3

END   14.7 14.7

CHANGE OF AVERAGE TEMPERATURE   -0.609 C

MIN. TEMPERATURE   10.6 C   MAX.TEMPERATURE   32.7 C

MIN CHANGE OF STORAGE   -825.04 MWH   MAX   3047.72 MWH

DIAMETER OF CENTRAL COLLECTOR ARRAY PIPES   0.300 M

INSULATION THICKNESS ROUND PIPES   0.050 M

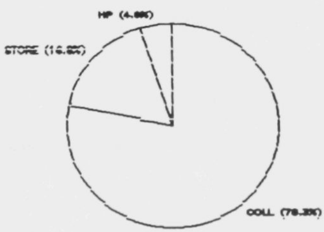
H E A T   P U M P   P E R F O R M A N C E

	EL-MOTOR	COND POWER	C.O.P.
TAP WATER	0.00	0.00	0.00
HOUSE HEAT	2217.27	9929.12	4.48

TOTAL SOLAR COST (/MWH DELIVERED FROM SOLAR/HP SYSTEM)   51.94

SYSTEM COST BREAKDOWN
(not included in MINSUN output file)

Capital Cost



Annualized Cost

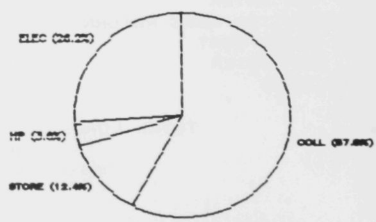


TABLE B.1 Results of MINSUN Simulation for Low-Temperature Distribution Using Flat Plate Collectors (Hartford, Conn.)

MINSUN Simulation Results: Hartford / Flat Plate / Low Temperature

AREA m^2	VOLUME m^3	BORE-HOLES	COLL SUPPLY MWH	STORAGE LOSS MWH	STORAGE SUPPLY MWH	HP ENERGY MWH	AUX ENERGY MWH	SOLAR FRACTION %	STORAGE TMIN C	STORAGE TMAX C	HP COP	HP COND MAX PWR MW	HP MTR MAX PWR MW	AUX MAX PWR MW
10000	200000	200	5331.17	185.54	5135.02	1518.54	3351.14	51.33	12.56	29.78	4.38	3.89	1.38	3.99
10000	200000	400	5717.64	90.30	5639.92	1688.96	2675.82	56.37	9.72	29.38	4.34	3.99	1.38	3.79
10000	200000	600	5787.88	54.26	5835.14	1744.09	2425.47	58.32	8.56	29.45	4.35	3.99	1.30	3.79
10000	200000	800	5825.97	47.85	5893.10	1748.97	2362.63	58.90	8.35	29.56	4.37	3.99	1.27	3.79
10000	200000	1000	5834.73	35.28	5942.35	1765.21	2297.14	59.40	8.02	29.51	4.37	3.99	1.25	3.79
15000	200000	200	7059.56	390.54	6337.36	1824.53	1842.81	63.34	12.65	35.66	4.47	3.99	1.38	3.79
15000	200000	400	7664.62	330.55	7262.34	1995.59	746.78	72.59	9.84	38.55	4.64	3.99	1.30	3.79
15000	200000	600	7805.94	317.14	7482.93	2023.55	498.22	74.79	8.91	38.81	4.70	3.99	1.23	3.79
15000	200000	800	7890.24	323.76	7562.46	2022.91	419.33	75.59	8.76	39.09	4.74	3.99	1.20	3.79
15000	200000	1000	7921.40	316.73	7620.02	2040.64	344.04	76.16	8.44	39.06	4.73	3.99	1.19	3.79
20000	200000	200	7894.43	452.83	7362.12	1963.76	678.81	73.59	13.78	41.75	4.75	3.99	1.27	3.79
20000	200000	400	8915.42	573.86	8150.69	1854.00	0.00	81.47	13.40	47.01	5.40	3.99	1.19	0.00
20000	200000	600	9092.74	617.22	8221.34	1783.36	0.00	82.18	13.76	47.57	5.61	3.99	1.11	0.00
20000	200000	800	9210.15	648.83	8256.31	1748.39	0.00	82.52	14.11	48.01	5.72	3.99	1.08	0.00
20000	200000	1000	9250.60	660.97	8270.51	1734.19	0.00	82.67	14.20	48.09	5.77	3.99	1.06	0.00
25000	200000	200	8590.35	547.30	7768.38	2011.13	225.19	77.65	14.63	43.15	4.86	3.99	1.26	3.79
25000	200000	400	9530.40	820.50	8504.54	1485.97	14.20	85.01	19.93	55.21	6.37	3.99	0.95	0.11
25000	200000	600	9796.01	887.84	8589.31	1409.11	6.27	85.85	20.55	56.14	6.63	3.99	0.91	0.07
25000	200000	800	9946.47	930.21	8627.01	1370.11	7.58	86.23	20.98	56.73	6.74	3.99	0.89	0.14
25000	200000	1000	10020.53	953.04	8645.87	1349.44	9.39	86.42	21.21	56.97	6.80	3.99	0.88	0.19
30000	200000	200	8854.59	598.70	8091.08	1913.61	.00	80.87	17.05	46.22	5.23	3.99	1.28	0.00
30000	200000	400	9976.25	1006.07	8784.53	1198.01	22.16	87.80	25.32	62.04	6.95	3.99	0.85	0.20
30000	200000	600	10317.23	1098.89	8867.56	1113.58	23.55	88.63	26.16	63.24	7.25	3.99	0.81	0.23
30000	200000	800	10514.23	1155.78	8911.03	1075.80	17.86	89.07	26.73	63.97	7.45	3.99	0.78	0.21
30000	200000	1000	10613.52	1185.49	8934.13	1055.29	15.28	89.30	27.01	64.31	7.54	3.99	0.77	0.17
10000	300000	200	5441.86	116.57	5436.17	1673.96	2894.56	54.34	12.88	26.14	4.25	3.89	1.41	3.99
10000	300000	400	5921.84	100.69	5828.65	1837.85	2338.20	58.26	9.82	24.23	4.17	3.99	1.41	3.79
10000	300000	600	6016.75	67.03	6064.40	1906.59	2033.72	60.62	8.95	24.38	4.18	3.99	1.32	3.79
10000	300000	800	6042.01	48.86	6171.97	1934.26	1898.47	61.69	8.55	24.38	4.19	3.99	1.28	3.79
10000	300000	1000	6061.45	40.91	6221.27	1942.84	1840.59	62.18	8.37	24.41	4.20	3.99	1.26	3.79
15000	300000	200	7231.76	320.14	6619.56	2002.66	1382.48	66.17	13.53	30.38	4.31	3.99	1.41	3.79
15000	300000	400	7911.14	272.01	7724.17	2204.95	75.57	77.21	10.74	32.90	4.50	3.99	1.35	3.15
15000	300000	600	8068.07	289.47	7850.39	2154.31	0.00	78.47	10.62	33.26	4.64	3.99	1.26	0.00
15000	300000	800	8119.85	297.55	7879.28	2125.42	0.00	78.76	10.66	33.34	4.71	3.99	1.23	0.00
15000	300000	1000	8152.11	303.30	7893.48	2111.21	.00	78.90	10.69	33.43	4.74	3.99	1.21	0.00
20000	300000	200	8293.87	440.97	7252.37	2137.25	615.08	72.49	14.32	32.18	4.39	3.99	1.30	3.79
20000	300000	400	9165.69	616.49	8163.70	1841.00	0.00	81.60	17.24	40.71	5.43	3.99	1.07	0.00
20000	300000	600	9393.49	674.97	8234.80	1769.89	0.00	82.31	17.61	41.30	5.65	3.99	0.99	0.00
20000	300000	800	9488.57	701.20	8263.33	1741.37	0.00	82.59	17.79	41.48	5.75	3.99	0.96	0.00
20000	300000	1000	9553.26	719.22	8278.49	1726.21	.00	82.75	17.92	41.64	5.80	3.99	0.94	0.00
25000	300000	200	8948.59	520.86	7576.14	2173.52	255.04	75.73	14.75	33.07	4.49	3.99	1.24	3.79
25000	300000	400	9784.93	906.38	8511.62	1493.07	0.00	85.08	23.79	48.67	6.70	3.99	0.89	0.00
25000	300000	600	10133.26	1000.53	8593.91	1410.80	0.00	85.90	24.45	49.54	7.09	3.99	0.85	0.00
25000	300000	800	10283.30	1045.70	8628.10	1376.60	.00	86.24	24.75	49.86	7.27	3.99	0.83	0.00
25000	300000	1000	10380.67	1074.55	8646.65	1358.05	0.00	86.43	24.94	50.10	7.37	3.99	0.82	0.00
30000	300000	200	9058.29	671.21	7972.10	2032.60	.00	79.68	18.49	37.40	4.92	3.99	1.26	0.00
30000	300000	400	10255.82	1129.16	8798.26	1194.19	12.26	87.94	29.30	55.15	7.85	3.99	0.78	0.09
30000	300000	600	10702.42	1248.64	8892.45	1094.77	17.48	88.88	30.14	56.36	8.27	3.99	0.74	0.24
30000	300000	800	10896.56	1305.46	8932.60	1052.73	19.36	89.28	30.55	56.83	8.44	3.99	0.72	0.16

TABLE B.1 (Cont'd)

30000	300000	1000	11028.88	1341.83	8960.72	1032.83	11.14	89.57	30.80	57.21	8.58	3.99	0.71	0.12
10000	400000	200	5507.68	147.09	5529.49	1745.13	2730.07	55.27	13.23	23.73	4.17	3.89	1.40	3.99
10000	400000	400	6005.06	41.27	6026.87	1957.79	2020.03	60.24	10.02	21.69	4.08	3.99	1.43	3.79
10000	400000	600	6113.23	0.04	6348.23	2047.41	1609.06	63.45	9.08	21.83	4.10	3.99	1.33	3.79
10000	400000	800	6144.53	-16.90	6463.87	2069.46	1471.37	64.61	8.73	21.86	4.12	3.99	1.29	3.79
10000	400000	1000	6152.86	-32.03	6550.46	2090.22	1364.01	65.47	8.40	21.84	4.13	3.99	1.28	3.79
15000	400000	200	7289.97	343.16	6616.59	2051.84	1336.27	66.14	14.18	26.95	4.23	3.99	1.47	3.89
15000	400000	400	8066.45	358.11	7755.82	2248.87	.00	77.52	12.16	29.23	4.45	3.99	1.31	0.00
15000	400000	600	8231.17	387.52	7833.79	2170.91	0.00	78.30	12.28	29.54	4.61	3.99	1.22	0.00
15000	400000	800	8296.18	400.91	7864.04	2140.65	.00	78.60	12.34	29.66	4.67	3.99	1.18	0.00
15000	400000	1000	8319.16	404.46	7876.67	2128.03	0.00	78.73	12.34	29.66	4.70	3.99	1.17	0.00
20000	400000	200	8328.35	443.04	7196.62	2205.45	602.63	71.93	14.83	28.31	4.26	3.99	1.38	3.79
20000	400000	400	9143.11	794.11	8185.10	1819.60	0.00	81.81	19.71	38.05	5.50	3.99	1.00	0.00
20000	400000	600	9405.48	862.91	8255.88	1748.82	0.00	82.52	20.07	38.55	5.72	3.99	0.93	0.00
20000	400000	800	9520.06	896.97	8285.01	1719.68	.00	82.81	20.23	38.76	5.82	3.99	0.92	0.00
20000	400000	1000	9572.91	912.87	8298.09	1706.61	0.00	82.94	20.31	38.81	5.86	3.99	0.91	0.00
25000	400000	200	8964.27	516.70	7453.51	2216.69	334.51	74.50	14.83	28.89	4.36	3.99	1.33	3.79
25000	400000	400	9799.42	1124.07	8528.89	1475.80	0.00	85.25	26.28	45.73	6.78	3.99	0.86	0.00
25000	400000	600	10180.69	1228.64	8608.84	1395.85	.00	86.05	26.85	46.47	7.17	3.99	0.81	0.00
25000	400000	800	10356.97	1282.59	8643.10	1361.58	.00	86.39	27.11	46.79	7.35	3.99	0.79	0.00
25000	400000	1000	10450.19	1311.61	8659.42	1345.29	.00	86.55	27.26	46.91	7.44	3.99	0.78	0.00
30000	400000	200	9423.29	555.94	7717.31	2287.39	0.00	77.14	14.83	29.17	4.37	3.99	1.36	0.00
30000	400000	400	10312.77	1386.90	8804.27	1200.42	.00	88.00	31.63	51.82	8.33	3.99	0.76	0.00
30000	400000	600	10810.30	1526.60	8894.65	1110.05	.00	88.91	32.36	52.83	9.01	3.99	0.71	0.00
30000	400000	800	11040.12	1597.91	8933.15	1071.55	0.00	89.29	32.71	53.27	9.34	3.99	0.69	0.00
30000	400000	1000	11170.99	1639.73	8952.93	1051.77	.00	89.49	32.92	53.48	9.51	3.99	0.68	0.00
10000	500000	200	5599.84	227.24	5402.90	1727.38	2874.42	54.00	13.49	21.57	4.13	3.89	1.41	3.99
10000	500000	400	6091.29	102.19	6008.15	1965.64	2030.92	60.05	10.23	19.61	4.06	3.99	1.47	3.89
10000	500000	600	6189.15	50.24	6399.45	2110.54	1494.70	63.96	9.23	19.71	4.03	3.99	1.37	3.79
10000	500000	800	6230.14	29.43	6564.22	2153.92	1286.57	65.61	8.80	19.75	4.05	3.99	1.33	3.79
10000	500000	1000	6250.59	21.24	6628.41	2167.71	1208.57	66.25	8.65	19.77	4.06	3.99	1.31	3.79
15000	500000	200	7377.61	410.12	6450.47	2035.84	1518.39	64.47	14.25	24.19	4.17	3.89	1.37	3.99
15000	500000	400	8155.85	352.40	7744.39	2260.31	0.00	77.41	13.31	26.99	4.43	3.99	1.28	0.00
15000	500000	600	8310.55	379.77	7820.19	2184.51	0.00	78.17	13.38	27.24	4.58	3.99	1.19	0.00
15000	500000	800	8387.34	395.24	7851.36	2153.33	.00	78.48	13.43	27.36	4.65	3.99	1.16	0.00
15000	500000	1000	8427.34	404.08	7866.63	2138.07	0.00	78.63	13.47	27.41	4.68	3.99	1.14	0.00
20000	500000	200	8398.33	494.77	7023.18	2213.05	768.47	70.20	14.25	25.21	4.17	3.99	1.47	3.89
20000	500000	400	9266.58	817.89	8165.34	1839.36	0.00	81.62	20.83	35.55	5.44	3.99	0.98	0.00
20000	500000	600	9524.07	886.27	8232.90	1771.80	.00	82.29	21.10	35.96	5.65	3.99	0.92	0.00
20000	500000	800	9655.22	924.45	8262.76	1741.94	0.00	82.59	21.25	36.16	5.74	3.99	0.91	0.00
20000	500000	1000	9730.34	948.11	8278.20	1726.49	0.00	82.74	21.35	36.26	5.80	3.99	0.90	0.00
25000	500000	200	9041.45	552.09	7319.90	2272.30	412.50	73.17	14.25	25.64	4.22	3.99	1.41	3.79
25000	500000	400	9932.09	1176.82	8507.93	1496.77	0.00	85.04	27.42	43.11	6.68	3.99	0.85	0.00
25000	500000	600	10325.95	1285.31	8585.22	1419.49	0.00	85.81	27.90	43.74	7.05	3.99	0.80	0.00
25000	500000	800	10522.76	1344.55	8619.37	1385.33	.00	86.15	28.15	44.03	7.22	3.99	0.78	0.00
25000	500000	1000	10639.43	1381.81	8637.42	1367.27	0.00	86.33	28.31	44.20	7.32	3.99	0.77	0.00
30000	500000	200	9503.08	595.54	7522.66	2302.57	179.47	75.19	14.25	25.87	4.27	3.99	1.39	3.79
30000	500000	400	10441.06	1458.99	8780.32	1224.39	.00	87.76	32.74	49.04	8.17	3.99	0.74	0.00
30000	500000	600	10980.09	1609.26	8869.20	1135.50	0.00	88.65	33.42	49.99	8.81	3.99	0.70	0.00
30000	500000	800	11230.16	1687.15	8907.32	1097.38	.00	89.03	33.74	50.39	9.12	3.99	0.68	0.00
30000	500000	1000	11384.65	1736.82	8927.87	1076.84	.00	89.24	33.95	50.62	9.29	3.99	0.67	0.00
10000	600000	200	5630.79	217.86	5408.92	1726.00	2869.78	54.06	13.73	20.50	4.13	3.05	0.92	3.99
10000	600000	400	6139.38	69.22	6093.38	2026.83	1884.50	60.91	10.39	18.43	4.01	3.89	1.37	3.99
10000	600000	600	6234.44	13.86	6539.59	2194.83	1270.29	65.37	9.41	18.52	3.98	3.99	1.39	3.79
10000	600000	800	6274.12	-9.97	6748.59	2251.93	1004.18	67.45	8.92	18.56	4.00	3.99	1.34	3.79

TABLE B.1 (Cont'd)

10000	600000	1000	6285.72	-19.87	6807.58	2262.69	934.43	68.04	8.80	18.57	4.01	3.99	1.32	3.79
15000	600000	200	7395.50	389.73	6374.92	2025.88	1603.90	63.72	14.25	22.70	4.15	3.89	1.39	3.99
15000	600000	400	8222.15	335.75	7727.40	2277.30	0.00	77.24	13.99	25.41	4.39	3.99	1.27	0.00
15000	600000	600	8380.32	365.63	7804.74	2199.96	0.00	78.01	14.06	25.62	4.55	3.99	1.18	0.00
15000	600000	800	8456.56	381.51	7836.01	2168.68	.00	78.32	14.11	25.73	4.61	3.99	1.14	0.00
15000	600000	1000	8486.99	390.02	7850.53	2154.17	.00	78.47	14.12	25.77	4.64	3.99	1.13	0.00
20000	600000	200	8393.86	469.25	6884.72	2181.81	938.17	68.82	14.25	23.50	4.16	3.89	1.34	3.99
20000	600000	400	9367.16	828.94	8145.15	1859.54	0.00	81.41	21.50	33.75	5.38	3.99	0.98	0.00
20000	600000	600	9628.66	901.30	8211.92	1792.78	0.00	82.08	21.73	34.11	5.58	3.99	0.92	0.00
20000	600000	800	9763.51	941.52	8241.49	1763.21	0.00	82.38	21.86	34.29	5.67	3.99	0.90	0.00
20000	600000	1000	9826.44	964.34	8255.45	1749.26	.00	82.52	21.92	34.36	5.72	3.99	0.89	0.00
25000	600000	200	9029.39	514.16	7225.40	2282.52	496.78	72.22	14.25	23.85	4.17	3.99	1.46	3.89
25000	600000	400	10041.25	1213.67	8486.40	1518.31	0.00	84.82	28.11	41.19	6.59	3.99	0.84	0.00
25000	600000	600	10453.95	1329.87	8562.97	1441.73	0.00	85.59	28.54	41.77	6.94	3.99	0.80	0.00
25000	600000	800	10654.25	1391.99	8596.08	1408.61	0.00	85.92	28.76	42.03	7.10	3.99	0.78	0.00
25000	600000	1000	10762.07	1429.23	8612.40	1392.30	0.00	86.08	28.87	42.15	7.19	3.99	0.77	0.00
30000	600000	200	9506.93	555.31	7425.87	2312.83	265.99	74.22	14.25	24.03	4.21	3.99	1.42	3.89
30000	600000	400	10544.98	1514.13	8756.45	1248.24	0.00	87.52	33.40	47.05	8.02	3.99	0.74	0.00
30000	600000	600	11125.59	1677.53	8845.61	1159.07	.00	88.42	34.06	47.95	8.63	3.99	0.69	0.00
30000	600000	800	11388.19	1760.27	8882.69	1122.00	.00	88.79	34.35	48.29	8.92	3.99	0.67	0.00
30000	600000	1000	11532.90	1810.36	8901.25	1103.45	.00	88.97	34.50	48.48	9.07	3.99	0.66	0.00

TABLE B.2 Results of MINSUN Simulation for Low-Temperature Distribution Using Unglazed Collectors (Hartford, Conn.)

MINSUN Simulation Results: Hartford / Unglazed / Low Temperature

AREA m^2	VOLUME m^3	BORE-HOLES	COLL SUPPLY MWH	STORAGE LOSS MWH	STORAGE SUPPLY MWH	HP ENERGY MWH	AUX ENERGY MWH	SOLAR FRACTION %	STORAGE TMIN C	STORAGE TMAX C	HP COP	HP COND MAX PWR MW	HP MTR MAX PWR MW	AUX MAX PWR MW
10000	200000	200	4440.74	131.33	4315.74	1277.60	4411.36	43.14	11.42	27.17	4.38	3.05	0.95	3.99
10000	200000	400	5044.41	82.71	4980.32	1479.80	3544.58	49.78	9.23	28.43	4.37	3.89	1.39	3.99
10000	200000	600	5210.91	63.85	5210.26	1551.77	3242.66	52.08	8.43	28.78	4.36	3.99	1.42	3.79
10000	200000	800	5289.25	56.37	5307.82	1575.63	3121.25	53.05	8.08	28.96	4.37	3.99	1.38	3.79
10000	200000	1000	5313.51	51.20	5352.73	1584.80	3067.17	53.50	7.82	29.01	4.38	3.99	1.37	3.79
15000	200000	200	5317.49	239.32	4903.22	1425.92	3675.56	49.01	11.73	30.22	4.44	3.65	1.26	3.99
15000	200000	400	6105.30	196.44	5874.05	1691.78	2438.87	58.71	9.42	33.27	4.47	3.99	1.33	3.79
15000	200000	600	6392.97	199.23	6146.29	1758.83	2099.58	61.43	8.68	33.93	4.50	3.99	1.24	3.79
15000	200000	800	6518.98	206.63	6246.14	1770.28	1988.28	62.43	8.33	34.27	4.53	3.99	1.20	3.79
15000	200000	1000	6582.11	206.70	6306.53	1790.71	1907.46	63.04	8.05	34.43	4.52	3.99	1.18	3.79
20000	200000	200	5873.25	296.28	5296.92	1544.75	3163.03	52.94	11.79	31.87	4.43	3.89	1.42	3.99
20000	200000	400	6823.96	243.75	6548.46	1838.97	1617.27	65.45	9.45	36.78	4.56	3.99	1.21	3.79
20000	200000	600	7172.12	274.96	6794.30	1866.06	1344.33	67.91	8.93	37.69	4.64	3.99	1.12	3.79
20000	200000	800	7370.54	288.94	6949.30	1894.01	1161.38	69.46	8.73	38.17	4.67	3.99	1.08	3.79
20000	200000	1000	7457.46	300.77	7007.02	1893.61	1104.07	70.04	8.59	38.42	4.70	3.99	1.06	3.79
25000	200000	200	6209.42	326.59	5559.67	1627.52	2817.51	55.57	11.75	32.87	4.42	3.89	1.40	3.99
25000	200000	400	7283.14	288.33	6961.36	1889.62	1153.71	69.58	9.74	39.46	4.68	3.99	1.12	3.79
25000	200000	600	7753.49	330.90	7304.01	1942.73	757.95	73.01	9.08	40.61	4.76	3.99	1.12	3.79
25000	200000	800	8019.18	353.76	7493.61	1993.75	517.35	74.90	8.81	41.21	4.76	3.99	1.28	3.79
25000	200000	1000	8163.74	367.19	7597.30	2015.81	391.58	75.94	8.58	41.54	4.77	3.99	1.26	3.79
30000	200000	200	6423.24	347.12	5704.71	1660.70	2639.28	57.02	11.84	33.41	4.44	3.89	1.38	3.99
30000	200000	400	7629.49	321.31	7271.90	1935.69	797.11	72.69	10.01	41.37	4.76	3.99	1.14	3.79
30000	200000	600	8225.67	376.12	7691.21	2025.23	288.26	76.88	9.07	42.70	4.80	3.99	1.26	3.79
30000	200000	800	8483.92	417.55	7820.70	2017.47	166.53	78.17	9.27	43.41	4.88	3.99	1.21	3.79
30000	200000	1000	8664.05	436.18	7948.38	2056.32	0.00	79.45	9.06	43.80	4.87	3.99	1.36	0.00
10000	300000	200	4690.95	93.04	4654.34	1432.09	3918.27	46.52	11.67	24.16	4.25	3.05	0.94	3.99
10000	300000	400	5359.32	19.98	5475.91	1702.60	2826.19	54.73	9.61	25.21	4.22	3.99	1.43	3.79
10000	300000	600	5556.96	-1.40	5768.72	1780.37	2455.61	57.66	8.77	25.61	4.24	3.99	1.34	3.79
10000	300000	800	5638.24	-16.79	5910.95	1823.69	2270.06	59.08	8.31	25.72	4.24	3.99	1.30	3.79
10000	300000	1000	5669.16	-19.12	5957.18	1825.58	2221.94	59.54	8.14	25.80	4.26	3.99	1.28	3.79
15000	300000	200	5675.51	204.84	5305.98	1611.64	3087.08	53.04	12.15	26.69	4.29	3.29	1.08	3.99
15000	300000	400	6578.94	160.46	6575.45	1960.10	1469.15	65.72	9.73	29.97	4.36	3.99	1.25	3.79
15000	300000	600	6894.56	173.14	6872.15	2005.72	1126.83	68.69	9.06	30.68	4.43	3.99	1.15	3.79
15000	300000	800	7042.11	171.13	7043.33	2053.02	908.35	70.40	8.63	30.94	4.43	3.99	1.29	3.79
15000	300000	1000	7119.02	175.34	7110.17	2065.64	828.89	71.07	8.50	31.11	4.44	3.99	1.27	3.79
20000	300000	200	6216.09	245.79	5708.80	1744.32	2551.58	57.06	12.03	27.77	4.27	3.89	1.39	3.99
20000	300000	400	7287.95	228.46	7267.52	2097.09	640.09	72.64	10.03	33.24	4.47	3.99	1.14	3.79
20000	300000	600	7736.81	263.82	7628.02	2143.44	233.23	76.24	9.33	34.22	4.56	3.99	1.21	3.79
20000	300000	800	7924.91	281.92	7767.37	2161.75	75.57	77.64	9.11	34.61	4.59	3.99	1.33	3.15
20000	300000	1000	8016.99	302.81	7790.20	2138.92	75.57	77.87	9.23	34.89	4.64	3.99	1.30	3.15
25000	300000	200	6492.83	277.31	5865.91	1785.75	2353.04	58.63	12.37	28.25	4.29	3.89	1.38	3.99
25000	300000	400	7745.86	287.30	7702.67	2135.50	166.53	76.99	10.64	35.79	4.61	3.99	1.22	3.79
25000	300000	600	8204.08	364.36	7911.10	2093.60	0.00	79.07	10.76	36.98	4.78	3.99	1.27	0.00
25000	300000	800	8394.73	410.29	7955.82	2048.88	.00	79.52	11.08	37.51	4.88	3.99	1.23	0.00
25000	300000	1000	8518.18	440.34	7980.62	2024.08	.00	79.77	11.27	37.86	4.94	3.99	1.21	0.00
30000	300000	200	6728.28	289.08	6061.39	1854.13	2089.18	60.59	12.30	28.53	4.27	3.89	1.37	3.99
30000	300000	400	8033.78	350.67	7901.59	2103.12	0.00	78.98	11.66	37.73	4.76	3.99	1.30	0.00
30000	300000	600	8531.30	465.23	8012.43	1992.26	0.00	80.09	12.41	39.16	5.02	3.99	1.20	0.00
30000	300000	800	8762.33	523.88	8059.74	1944.96	0.00	80.56	12.82	39.81	5.14	3.99	1.16	0.00

TABLE B.2 (Cont'd)

30000	300000	1000	8912.45	562.16	8086.26	1918.43	0.00	80.83	13.08	40.23	5.22	3.99	1.14	0.00
10000	400000	200	4860.76	178.79	4693.13	1474.29	3837.28	46.91	12.15	21.87	4.18	3.05	0.93	3.99
10000	400000	400	5733.18	94.90	5639.81	1818.32	2546.57	56.37	9.67	22.18	4.10	3.99	1.46	3.79
10000	400000	600	5950.63	74.06	5991.06	1916.82	2096.81	59.88	8.83	22.57	4.13	3.99	1.36	3.79
10000	400000	800	6038.50	62.81	6150.40	1960.93	1893.37	61.48	8.41	22.71	4.14	3.99	1.31	3.79
10000	400000	1000	6067.83	58.26	6202.09	1965.56	1837.05	61.99	8.27	22.75	4.16	3.99	1.29	3.79
15000	400000	200	5902.34	281.98	5415.64	1683.06	2906.00	54.13	12.49	23.92	4.22	3.65	1.26	3.99
15000	400000	400	6843.51	137.85	7010.33	2134.71	859.66	70.07	10.29	27.63	4.28	3.99	1.24	3.79
15000	400000	600	7227.90	139.46	7467.78	2245.03	291.89	74.64	9.28	28.32	4.33	3.99	1.24	3.79
15000	400000	800	7387.85	143.50	7648.44	2280.69	75.57	76.45	8.89	28.62	4.35	3.99	1.34	3.15
15000	400000	1000	7441.83	151.91	7668.55	2260.57	75.57	76.65	8.93	28.74	4.39	3.99	1.32	3.15
20000	400000	200	6391.62	326.23	5702.92	1764.79	2537.00	57.00	12.74	24.68	4.23	3.29	1.07	3.99
20000	400000	400	7564.98	233.67	7685.99	2243.14	75.57	76.82	11.12	30.84	4.43	3.99	1.35	3.15
20000	400000	600	7959.91	306.37	7841.01	2163.70	0.00	78.37	11.35	31.83	4.62	3.99	1.25	0.00
20000	400000	800	8137.56	346.01	7884.43	2120.27	0.00	78.81	11.58	32.29	4.72	3.99	1.21	0.00
20000	400000	1000	8228.19	365.76	7904.79	2099.91	0.00	79.01	11.70	32.49	4.76	3.99	1.19	0.00
25000	400000	200	6678.48	353.43	5871.59	1817.78	2315.32	58.69	12.92	24.99	4.23	3.89	1.40	3.99
25000	400000	400	8193.27	423.68	7828.02	2176.68	0.00	78.24	12.37	32.60	4.60	3.99	1.29	0.00
25000	400000	600	8682.27	537.03	7937.64	2067.05	0.00	79.34	12.99	33.88	4.84	3.99	1.19	0.00
25000	400000	800	8916.10	595.77	7983.38	2021.32	0.00	79.80	13.32	34.49	4.95	3.99	1.14	0.00
25000	400000	1000	9047.61	629.39	8007.20	1997.49	.00	80.03	13.52	34.79	5.01	3.99	1.12	0.00
30000	400000	200	6905.49	360.93	6059.22	1885.94	2059.53	60.56	12.92	25.13	4.21	3.89	1.39	3.99
30000	400000	400	8381.97	507.15	7923.84	2080.86	0.00	79.20	13.87	34.60	4.81	3.99	1.22	0.00
30000	400000	600	8960.65	646.05	8036.04	1968.66	0.00	80.32	14.65	36.10	5.08	3.99	1.12	0.00
30000	400000	800	9241.21	718.53	8084.67	1920.03	.00	80.81	15.06	36.81	5.21	3.99	1.07	0.00
30000	400000	1000	9404.46	762.18	8110.60	1894.10	0.00	81.07	15.32	37.19	5.28	3.99	1.05	0.00
10000	500000	200	4949.20	166.80	4745.13	1504.03	3755.54	47.43	12.51	20.47	4.16	3.05	0.93	3.99
10000	500000	400	5891.99	54.32	5910.07	1943.02	2151.61	59.07	9.70	20.59	4.04	3.99	1.47	3.79
10000	500000	600	6103.27	29.33	6290.56	2055.29	1658.84	62.88	8.92	20.93	4.06	3.99	1.36	3.79
10000	500000	800	6197.62	16.17	6485.17	2100.31	1419.22	64.82	8.46	21.08	4.09	3.99	1.32	3.79
10000	500000	1000	6238.97	13.50	6545.95	2109.14	1349.61	65.43	8.36	21.15	4.10	3.99	1.29	3.79
15000	500000	200	6000.55	263.26	5447.13	1728.75	2828.81	54.45	12.92	22.15	4.15	3.89	1.42	3.99
15000	500000	400	7321.42	232.31	7159.61	2260.04	585.05	71.56	10.49	24.94	4.17	3.99	1.29	3.79
15000	500000	600	7704.02	249.76	7584.64	2344.49	75.57	75.81	9.79	25.60	4.24	3.99	1.35	3.15
15000	500000	800	7853.91	271.96	7679.38	2325.31	0.00	76.76	9.74	25.91	4.30	3.99	1.31	0.00
15000	500000	1000	7927.50	287.20	7702.22	2302.47	0.00	76.99	9.81	26.07	4.35	3.99	1.29	0.00
20000	500000	200	6471.46	310.22	5686.36	1779.93	2538.41	56.84	12.92	22.70	4.20	3.65	1.25	3.99
20000	500000	400	7999.12	379.38	7725.33	2279.37	0.00	77.22	12.17	28.37	4.39	3.99	1.32	0.00
20000	500000	600	8413.85	469.26	7831.03	2173.67	0.00	78.27	12.59	29.32	4.60	3.99	1.22	0.00
20000	500000	800	8622.22	518.34	7875.86	2128.84	0.00	78.72	12.82	29.79	4.70	3.99	1.17	0.00
20000	500000	1000	8738.98	547.65	7898.61	2106.09	0.00	78.95	12.96	30.06	4.75	3.99	1.15	0.00
25000	500000	200	6787.69	326.10	5919.52	1860.47	2224.71	59.17	12.92	22.93	4.18	3.29	1.08	3.99
25000	500000	400	8362.22	461.13	7845.77	2158.93	0.00	78.42	14.04	30.67	4.63	3.99	1.24	0.00
25000	500000	600	8890.81	585.16	7953.80	2050.90	0.00	79.50	14.67	31.90	4.88	3.99	1.13	0.00
25000	500000	800	9163.52	653.42	8001.10	2003.60	0.00	79.97	15.01	32.53	4.99	3.99	1.09	0.00
25000	500000	1000	9318.96	694.47	8025.83	1978.88	0.00	80.22	15.22	32.88	5.06	3.99	1.06	0.00
30000	500000	200	6994.04	340.80	6035.06	1901.47	2068.18	60.32	12.92	23.03	4.17	3.89	1.42	3.99
30000	500000	400	8543.50	546.88	7936.00	2068.70	0.00	79.32	15.50	32.55	4.84	3.99	1.17	0.00
30000	500000	600	9192.95	703.74	8049.64	1955.06	.00	80.46	16.34	34.06	5.12	3.99	1.06	0.00
30000	500000	800	9517.89	787.77	8099.43	1905.27	0.00	80.96	16.77	34.80	5.25	3.99	1.02	0.00
30000	500000	1000	9710.50	839.51	8126.42	1878.28	0.00	81.23	17.04	35.23	5.33	3.99	0.99	0.00
10000	600000	200	5011.36	156.06	4758.03	1513.00	3733.67	47.56	12.77	19.45	4.15	3.05	0.95	3.99
10000	600000	400	5992.12	29.41	6012.07	1983.84	2008.79	60.09	10.04	19.40	4.03	3.99	1.48	3.89
10000	600000	600	6221.06	-6.30	6507.03	2158.40	1339.26	65.04	9.11	19.72	4.02	3.99	1.37	3.79
10000	600000	800	6309.78	-16.09	6675.40	2192.27	1137.03	66.72	8.82	19.86	4.05	3.99	1.33	3.79

TABLE B.2 (Cont'd)

10000	600000	1000	6353.79	-25.80	6789.76	2228.37	986.58	67.87	8.58	19.92	4.05	3.99	1.30	3.79
15000	600000	200	6038.94	249.27	5373.85	1700.88	2929.97	53.71	12.92	20.84	4.16	3.05	0.92	3.99
15000	600000	400	7450.62	223.61	7236.79	2291.41	476.49	72.33	11.20	23.53	4.16	3.99	1.31	3.79
15000	600000	600	7828.97	248.95	7640.39	2364.31	0.00	76.37	10.68	24.13	4.23	3.99	1.32	0.00
15000	600000	800	7976.42	278.19	7685.38	2319.33	.00	76.82	10.80	24.43	4.31	3.99	1.28	0.00
15000	600000	1000	8049.78	295.12	7707.67	2297.03	0.00	77.04	10.86	24.58	4.36	3.99	1.25	0.00
20000	600000	200	6549.56	283.38	5704.41	1811.83	2488.45	57.02	12.92	21.26	4.15	3.65	1.28	3.99
20000	600000	400	8134.48	392.82	7728.55	2276.16	0.00	77.25	13.25	26.90	4.40	3.99	1.29	0.00
20000	600000	600	8578.34	490.73	7833.89	2170.80	.00	78.30	13.68	27.81	4.61	3.99	1.19	0.00
20000	600000	800	8802.77	543.60	7878.55	2126.15	0.00	78.75	13.92	28.26	4.71	3.99	1.14	0.00
20000	600000	1000	8919.52	573.83	7900.50	2104.19	0.00	78.97	14.04	28.49	4.76	3.99	1.12	0.00
25000	600000	200	6826.74	311.71	5811.68	1827.87	2365.14	58.09	12.92	21.43	4.18	3.65	1.26	3.99
25000	600000	400	8522.28	478.03	7846.70	2158.00	0.00	78.43	15.12	29.15	4.64	3.99	1.21	0.00
25000	600000	600	9105.31	616.15	7956.51	2048.19	0.00	79.53	15.79	30.37	4.89	3.99	1.10	0.00
25000	600000	800	9402.92	690.52	8003.63	2001.07	0.00	80.00	16.14	30.97	5.00	3.99	1.06	0.00
25000	600000	1000	9566.38	734.71	8027.96	1976.74	0.00	80.24	16.34	31.30	5.06	3.99	1.03	0.00
30000	600000	200	7029.51	324.60	5926.56	1867.32	2210.82	59.24	12.92	21.54	4.17	3.65	1.25	3.99
30000	600000	400	8710.80	568.48	7934.98	2069.72	.00	79.31	16.60	30.96	4.83	3.99	1.14	0.00
30000	600000	600	9436.18	744.44	8050.72	1953.99	0.00	80.47	17.49	32.47	5.12	3.99	1.03	0.00
30000	600000	800	9791.97	835.44	8100.58	1904.12	0.00	80.97	17.93	33.18	5.25	3.99	0.99	0.00
30000	600000	1000	9999.58	892.48	8127.71	1876.99	0.00	81.24	18.19	33.60	5.33	3.99	0.96	0.00

TABLE B.3 Results of MINSUN Simulation for High-Temperature Distribution Using Flat Plate Collectors (Hartford, Conn.)

MINSUN Simulation Results: Hartford / Flat Plate / High Temperature

AREA m^2	VOLUME m^3	BORE-HOLES	COLL SUPPLY MWH	STORAGE LOSS MWH	STORAGE SUPPLY MWH	HP ENERGY MWH	AUX ENERGY MWH	SOLAR FRACTION %	STORAGE TMIN C	STORAGE TMAX C	HP COP	HP COND MAX PWR MW	HP MTR MAX PWR MW	AUX MAX PWR MW
10000	200000	200	5201.83	232.61	4996.10	4917.64	90.96	49.94	12.08	31.12	2.02	3.99	3.62	3.79
10000	200000	400	5454.21	220.76	5264.38	4649.36	90.96	52.62	11.26	31.65	2.13	3.99	3.47	3.79
10000	200000	600	5500.85	214.60	5335.11	4578.63	90.96	53.33	11.00	31.71	2.17	3.99	3.44	3.79
10000	200000	800	5537.27	216.37	5371.69	4542.05	90.96	53.69	10.94	31.82	2.18	3.99	3.41	3.79
10000	200000	1000	5543.16	213.77	5384.18	4529.56	90.96	53.82	10.88	31.77	2.19	3.99	3.41	3.79
15000	200000	200	6531.52	503.05	5884.46	4120.25	0.00	58.82	16.68	39.66	2.43	3.99	3.30	0.00
15000	200000	400	7011.53	563.54	6290.33	3714.37	0.00	62.87	16.52	41.90	2.69	3.99	3.14	0.00
15000	200000	600	7129.23	580.65	6382.81	3621.89	0.00	63.80	16.43	42.15	2.76	3.99	3.10	0.00
15000	200000	800	7207.98	596.01	6429.87	3574.83	0.00	64.27	16.49	42.41	2.80	3.99	3.08	0.00
15000	200000	1000	7225.20	599.04	6445.45	3559.25	0.00	64.42	16.46	42.40	2.81	3.99	3.08	0.00
20000	200000	200	7256.96	653.10	6463.36	3541.34	0.00	64.60	20.55	45.52	2.83	3.99	2.93	0.00
20000	200000	400	8022.08	806.45	7041.84	2962.86	0.00	70.39	21.88	50.95	3.38	3.99	2.60	0.00
20000	200000	600	8220.63	850.51	7149.87	2854.83	0.00	71.47	22.01	51.52	3.50	3.99	2.51	0.00
20000	200000	800	8336.31	878.39	7200.97	2803.72	.00	71.98	22.18	51.92	3.57	3.99	2.47	0.00
20000	200000	1000	8381.59	890.52	7223.03	2781.67	0.00	72.20	22.21	52.02	3.60	3.99	2.46	0.00
25000	200000	200	7723.96	755.70	6832.38	3172.32	0.00	68.29	23.52	49.31	3.15	3.99	2.69	0.00
25000	200000	400	8733.17	1007.65	7557.02	2447.67	0.00	75.54	26.64	58.36	4.09	3.99	2.19	0.00
25000	200000	600	9011.28	1079.74	7667.95	2336.75	.00	76.64	27.06	59.23	4.28	3.99	2.08	0.00
25000	200000	800	9170.60	1123.21	7718.32	2286.38	.00	77.15	27.39	59.78	4.38	3.99	2.03	0.00
25000	200000	1000	9249.56	1146.87	7744.44	2260.26	.00	77.41	27.54	60.01	4.43	3.99	2.00	0.00
30000	200000	200	8048.39	832.70	7086.78	2917.92	0.00	70.84	25.84	51.87	3.43	3.99	2.45	0.00
30000	200000	400	9268.98	1182.05	7916.42	2088.27	0.00	79.13	31.04	64.44	4.79	3.99	1.85	0.00
30000	200000	600	9606.01	1276.76	8019.14	1985.55	0.00	80.15	31.67	65.53	5.04	3.99	1.75	0.00
30000	200000	800	9802.70	1334.61	8069.09	1935.61	0.00	80.65	32.14	66.24	5.17	3.99	1.70	0.00
30000	200000	1000	9903.88	1366.31	8094.75	1909.95	0.00	80.91	32.37	66.53	5.24	3.99	1.67	0.00
35000	200000	200	8424.63	960.59	7106.67	2898.02	.00	71.03	26.24	51.01	3.45	3.99	2.41	0.00
35000	200000	400	9841.00	1384.78	8123.26	1881.44	0.00	81.19	34.25	68.43	5.32	3.99	1.66	0.00
35000	200000	600	9881.07	1417.88	8312.38	1692.32	.00	83.09	36.17	71.79	5.91	3.99	1.49	0.00
35000	200000	800	10109.63	1486.57	8361.23	1643.47	0.00	83.57	36.78	72.57	6.09	3.99	1.44	0.00
35000	200000	1000	10233.95	1526.61	8387.49	1617.21	0.00	83.84	37.09	72.96	6.19	3.99	1.42	0.00
10000	300000	200	5300.87	224.51	5043.95	4960.75	0.00	50.42	13.92	27.15	2.02	3.99	3.65	0.00
10000	300000	400	5557.20	207.59	5347.19	4657.51	0.00	53.45	13.08	27.50	2.15	3.99	3.59	0.00
10000	300000	600	5631.38	206.92	5442.38	4562.32	0.00	54.40	12.87	27.64	2.19	3.99	3.59	0.00
10000	300000	800	5649.92	203.78	5477.66	4527.04	0.00	54.75	12.77	27.64	2.21	3.99	3.60	0.00
10000	300000	1000	5663.40	203.46	5495.76	4508.93	0.00	54.93	12.72	27.67	2.22	3.99	3.60	0.00
15000	300000	200	6664.43	507.47	5909.41	4095.29	0.00	59.07	18.74	34.48	2.44	3.99	3.15	0.00
15000	300000	400	7202.58	586.79	6361.71	3642.99	0.00	63.59	18.79	36.63	2.75	3.99	2.95	0.00
15000	300000	600	7359.07	615.00	6472.53	3532.16	0.00	64.70	18.74	36.96	2.83	3.99	2.88	0.00
15000	300000	800	7407.80	624.58	6512.87	3491.83	0.00	65.10	18.69	37.01	2.87	3.99	2.86	0.00
15000	300000	1000	7444.05	632.59	6534.31	3470.39	.00	65.31	18.68	37.09	2.88	3.99	2.85	0.00
20000	300000	200	7358.94	662.94	6473.36	3531.34	0.00	64.70	22.70	39.77	2.83	3.99	2.82	0.00
20000	300000	400	8258.82	872.25	7112.29	2892.41	0.00	71.09	24.59	45.24	3.46	3.99	2.40	0.00
20000	300000	600	8505.70	930.63	7228.38	2776.32	0.00	72.25	24.78	45.79	3.60	3.99	2.30	0.00
20000	300000	800	8611.72	959.18	7275.24	2729.47	.00	72.72	24.88	45.98	3.67	3.99	2.26	0.00
20000	300000	1000	8674.13	976.14	7298.01	2706.69	0.00	72.95	24.93	46.12	3.70	3.99	2.24	0.00
25000	300000	200	7764.68	762.96	6813.54	3191.15	0.00	68.10	25.55	43.12	3.14	3.99	2.59	0.00
25000	300000	400	8999.79	1112.05	7608.81	2395.88	0.00	76.05	29.80	52.29	4.18	3.99	1.97	0.00
25000	300000	600	9325.79	1200.24	7715.44	2289.25	.00	77.12	30.20	53.10	4.37	3.99	1.88	0.00
25000	300000	800	9477.01	1245.46	7759.53	2245.16	.00	77.56	30.43	53.41	4.46	3.99	1.83	0.00

TABLE B.3 (Cont'd)

25000	300000	1000	9574.18	1274.53	7782.81	2221.89	0.00	77.79	30.59	53.65	4.50	3.99	1.81	0.00
30000	300000	200	8089.46	847.17	7060.46	2944.24	0.00	70.57	27.92	45.47	3.40	3.99	2.35	0.00
30000	300000	400	9540.26	1316.68	7943.77	2060.93	0.00	79.40	34.42	58.14	4.85	3.99	1.68	0.00
30000	300000	600	9969.04	1438.34	8049.51	1955.19	.00	80.46	35.11	59.25	5.12	3.99	1.57	0.00
30000	300000	800	10163.31	1499.56	8093.34	1911.36	0.00	80.90	35.46	59.68	5.23	3.99	1.52	0.00
30000	300000	1000	10298.16	1541.31	8119.08	1885.63	0.00	81.15	35.71	60.03	5.31	3.99	1.50	0.00
35000	300000	200	7993.02	972.61	7468.16	2536.53	0.00	74.65	32.13	51.59	3.94	3.99	2.06	0.00
35000	300000	400	10423.06	1608.21	8071.95	1932.74	0.00	80.68	36.66	60.34	5.18	3.99	1.56	0.00
35000	300000	600	10371.34	1739.26	8312.73	1691.96	.00	83.09	39.43	64.80	5.91	3.99	1.35	0.00
35000	300000	800	10610.02	1815.98	8356.35	1648.35	.00	83.52	39.90	65.33	6.07	3.99	1.30	0.00
35000	300000	1000	10775.60	1867.72	8382.01	1622.68	0.00	83.78	40.22	65.74	6.17	3.99	1.28	0.00
10000	400000	200	5346.94	327.43	5018.96	4985.74	0.00	50.17	14.86	24.89	2.01	3.99	3.71	0.00
10000	400000	400	5623.58	321.25	5324.66	4680.04	0.00	53.22	13.98	24.98	2.14	3.99	3.57	0.00
10000	400000	600	5704.82	325.06	5428.97	4575.73	0.00	54.26	13.79	25.11	2.19	3.99	3.52	0.00
10000	400000	800	5729.89	325.95	5469.96	4534.74	0.00	54.67	13.69	25.14	2.21	3.99	3.52	0.00
10000	400000	1000	5736.01	324.15	5487.82	4516.88	.00	54.85	13.64	25.11	2.22	3.99	3.52	0.00
15000	400000	200	6644.61	616.82	5928.38	4076.31	0.00	59.26	20.10	32.25	2.45	3.99	3.14	0.00
15000	400000	400	7233.24	714.90	6419.01	3585.69	0.00	64.16	20.35	34.32	2.79	3.99	2.84	0.00
15000	400000	600	7396.38	748.40	6533.89	3470.80	0.00	65.31	20.29	34.59	2.88	3.99	2.77	0.00
15000	400000	800	7464.01	765.48	6580.85	3423.85	0.00	65.78	20.26	34.70	2.92	3.99	2.73	0.00
15000	400000	1000	7487.46	771.30	6600.01	3404.69	0.00	65.97	20.23	34.69	2.94	3.99	2.72	0.00
20000	400000	200	7322.49	791.54	6453.72	3550.97	0.00	64.51	23.89	36.94	2.82	3.99	2.78	0.00
20000	400000	400	8309.12	1049.04	7156.07	2848.63	0.00	71.53	26.38	42.55	3.51	3.99	2.30	0.00
20000	400000	600	8573.19	1116.32	7270.77	2733.92	.00	72.67	26.53	43.00	3.66	3.99	2.20	0.00
20000	400000	800	8692.81	1151.78	7317.79	2686.90	.00	73.14	26.61	43.20	3.72	3.99	2.15	0.00
20000	400000	1000	8747.22	1168.81	7338.24	2666.45	0.00	73.35	26.65	43.24	3.75	3.99	2.13	0.00
25000	400000	200	7744.19	911.59	6779.95	3224.74	0.00	67.77	26.63	39.95	3.10	3.99	2.55	0.00
25000	400000	400	9067.10	1332.44	7627.56	2377.14	0.00	76.24	31.70	49.28	4.21	3.99	1.89	0.00
25000	400000	600	9427.94	1434.67	7731.10	2273.60	0.00	77.28	32.09	49.97	4.40	3.99	1.78	0.00
25000	400000	800	9595.77	1488.18	7773.70	2231.00	0.00	77.70	32.27	50.27	4.48	3.99	1.74	0.00
25000	400000	1000	9688.78	1518.38	7794.02	2210.67	.00	77.90	32.39	50.39	4.53	3.99	1.72	0.00
30000	400000	200	8057.75	1004.84	7012.40	2992.29	0.00	70.09	28.85	42.13	3.34	3.99	2.37	0.00
30000	400000	400	9623.61	1574.35	7952.65	2052.06	.00	79.49	36.40	54.95	4.88	3.99	1.60	0.00
30000	400000	600	10100.40	1712.83	8055.26	1949.44	0.00	80.52	37.03	55.90	5.13	3.99	1.49	0.00
30000	400000	800	10325.26	1785.15	8097.84	1906.85	0.00	80.94	37.33	56.32	5.25	3.99	1.45	0.00
30000	400000	1000	10453.67	1827.79	8119.46	1885.24	0.00	81.16	37.53	56.51	5.31	3.99	1.43	0.00
35000	400000	200	7967.54	1097.14	7445.17	2559.53	0.00	74.42	33.54	48.36	3.91	3.99	2.02	0.00
35000	400000	400	10636.16	1768.71	8030.32	1974.37	0.00	80.27	37.94	55.96	5.07	3.99	1.52	0.00
35000	400000	600	11312.02	1966.09	8151.25	1853.45	0.00	81.47	38.11	57.47	5.40	3.99	1.40	0.00
35000	400000	800	10886.81	2051.60	8339.28	1665.42	0.00	83.35	41.59	61.36	6.01	3.99	1.25	0.00
35000	400000	1000	11058.02	2107.58	8362.53	1642.17	0.00	83.59	41.88	61.64	6.09	3.99	1.22	0.00
10000	500000	200	5382.54	327.32	4985.97	5018.72	0.00	49.84	15.44	23.40	1.99	3.99	3.76	0.00
10000	500000	400	5668.32	322.19	5306.51	4698.19	0.00	53.04	14.63	23.43	2.13	3.99	3.62	0.00
10000	500000	600	5739.58	325.17	5413.02	4591.67	0.00	54.11	14.44	23.52	2.18	3.99	3.56	0.00
10000	500000	800	5769.39	326.82	5458.36	4546.33	0.00	54.56	14.35	23.55	2.20	3.99	3.53	0.00
10000	500000	1000	5785.31	328.52	5481.22	4523.48	0.00	54.79	14.31	23.57	2.21	3.99	3.52	0.00
15000	500000	200	6679.69	627.20	5886.99	4117.70	0.00	58.84	20.71	30.32	2.43	3.99	3.20	0.00
15000	500000	400	7311.94	738.44	6400.85	3603.86	0.00	63.98	21.10	32.30	2.78	3.99	2.80	0.00
15000	500000	600	7472.11	773.39	6517.65	3487.05	0.00	65.15	21.02	32.53	2.87	3.99	2.72	0.00
15000	500000	800	7549.77	793.34	6568.12	3436.58	0.00	65.65	21.00	32.63	2.91	3.99	2.69	0.00
15000	500000	1000	7592.35	805.78	6593.62	3411.08	0.00	65.91	21.00	32.68	2.93	3.99	2.68	0.00
20000	500000	200	7328.84	808.51	6407.61	3597.08	0.00	64.05	24.48	34.80	2.78	3.99	2.86	0.00
20000	500000	400	8413.76	1099.10	7139.76	2864.93	0.00	71.36	27.24	40.28	3.49	3.99	2.26	0.00
20000	500000	600	8677.02	1168.51	7252.14	2752.57	0.00	72.49	27.35	40.65	3.64	3.99	2.16	0.00
20000	500000	800	8810.27	1208.28	7300.34	2704.36	0.00	72.97	27.43	40.82	3.70	3.99	2.11	0.00

TABLE B.3 (Cont'd)

20000	500000	1000	8884.97	1232.91	7324.67	2680.03	0.00	73.21	27.49	40.92	3.73	3.99	2.09	0.00
25000	500000	200	7740.53	936.05	6734.22	3270.47	0.00	67.31	27.20	37.76	3.06	3.99	2.62	0.00
25000	500000	400	9193.10	1406.62	7607.28	2397.41	0.00	76.04	32.64	46.85	4.17	3.99	1.85	0.00
25000	500000	600	9563.57	1514.08	7707.95	2296.76	.00	77.04	32.97	47.44	4.36	3.99	1.75	0.00
25000	500000	800	9747.37	1573.19	7750.53	2254.18	0.00	77.47	33.14	47.71	4.44	3.99	1.71	0.00
25000	500000	1000	9861.51	1611.39	7773.10	2231.60	0.00	77.69	33.27	47.87	4.48	3.99	1.69	0.00
30000	500000	200	8053.46	1037.24	6969.22	3035.48	0.00	69.66	29.40	39.95	3.30	3.99	2.45	0.00
30000	500000	400	9761.51	1669.87	7931.50	2073.19	.00	79.28	37.38	52.39	4.83	3.99	1.57	0.00
30000	500000	600	10254.01	1814.82	8030.37	1974.32	.00	80.27	37.93	53.22	5.07	3.99	1.47	0.00
30000	500000	800	10501.26	1894.23	8072.39	1932.29	.00	80.69	38.21	53.60	5.18	3.99	1.42	0.00
30000	500000	1000	10650.03	1944.17	8094.45	1910.24	.00	80.91	38.39	53.80	5.24	3.99	1.40	0.00
35000	500000	200	7911.62	1217.77	7448.38	2556.31	0.00	74.45	34.69	46.79	3.91	3.99	2.06	0.00
35000	500000	400	10749.05	1901.46	8009.63	1995.07	.00	80.06	38.80	53.45	5.02	3.99	1.49	0.00
35000	500000	600	11469.99	2109.91	8125.80	1878.90	.00	81.22	38.80	54.81	5.33	3.99	1.38	0.00
35000	500000	800	11786.15	2212.32	8170.58	1834.12	.00	81.67	38.80	55.30	5.46	3.99	1.33	0.00
35000	500000	1000	11281.19	2304.68	8336.87	1667.82	0.00	83.33	42.71	58.86	6.00	3.99	1.20	0.00
10000	600000	200	5409.49	323.55	4949.03	5055.68	0.00	49.47	15.80	22.34	1.98	3.99	3.80	0.00
10000	600000	400	5704.58	317.25	5279.97	4724.73	0.00	52.78	15.05	22.32	2.12	3.99	3.66	0.00
10000	600000	600	5771.56	322.37	5390.48	4614.22	0.00	53.88	14.86	22.40	2.17	3.99	3.60	0.00
10000	600000	800	5800.74	324.96	5438.52	4566.18	0.00	54.36	14.78	22.43	2.19	3.99	3.58	0.00
10000	600000	1000	5809.66	326.94	5460.95	4543.76	0.00	54.58	14.73	22.44	2.20	3.99	3.56	0.00
15000	600000	200	6697.66	632.26	5842.89	4161.80	0.00	58.40	21.07	28.94	2.40	3.99	3.26	0.00
15000	600000	400	7380.96	754.79	6375.28	3629.41	0.00	63.72	21.58	30.88	2.76	3.99	2.86	0.00
15000	600000	600	7541.32	793.68	6495.77	3508.92	0.00	64.93	21.50	31.07	2.85	3.99	2.74	0.00
15000	600000	800	7619.13	815.54	6548.01	3456.68	0.00	65.45	21.48	31.16	2.89	3.99	2.69	0.00
15000	600000	1000	7651.74	828.23	6572.08	3432.62	.00	65.69	21.46	31.20	2.92	3.99	2.66	0.00
20000	600000	200	7330.84	822.96	6363.59	3641.09	0.00	63.61	24.83	33.34	2.75	3.99	2.91	0.00
20000	600000	400	8500.81	1137.39	7116.65	2888.04	0.00	71.13	27.77	38.65	3.46	3.99	2.25	0.00
20000	600000	600	8766.04	1212.13	7229.49	2775.20	0.00	72.26	27.87	38.97	3.61	3.99	2.15	0.00
20000	600000	800	8900.02	1254.71	7277.92	2726.78	0.00	72.75	27.93	39.12	3.67	3.99	2.10	0.00
20000	600000	1000	8964.48	1279.66	7300.47	2704.23	0.00	72.97	27.95	39.19	3.70	3.99	2.08	0.00
25000	600000	200	7731.43	957.72	6691.78	3312.92	0.00	66.89	27.54	36.26	3.02	3.99	2.68	0.00
25000	600000	400	9298.09	1466.08	7584.02	2420.68	.00	75.81	33.22	45.09	4.13	3.99	1.85	0.00
25000	600000	600	9680.04	1581.35	7684.24	2320.47	.00	76.81	33.52	45.63	4.31	3.99	1.74	0.00
25000	600000	800	9872.98	1645.39	7726.77	2277.93	0.00	77.23	33.67	45.86	4.39	3.99	1.70	0.00
25000	600000	1000	9977.00	1684.33	7747.45	2257.25	0.00	77.44	33.75	45.98	4.43	3.99	1.68	0.00
30000	600000	200	8047.40	1067.09	6930.32	3074.37	0.00	69.27	29.73	38.45	3.25	3.99	2.50	0.00
30000	600000	400	9857.25	1744.27	7905.86	2098.85	.00	79.02	37.95	50.52	4.77	3.99	1.57	0.00
30000	600000	600	10379.43	1900.22	8004.95	1999.76	0.00	80.01	38.46	51.28	5.00	3.99	1.46	0.00
30000	600000	800	10635.00	1984.62	8045.94	1958.77	0.00	80.42	38.70	51.61	5.11	3.99	1.42	0.00
30000	600000	1000	10779.22	2037.39	8066.70	1938.00	0.00	80.63	38.84	51.79	5.16	3.99	1.39	0.00
35000	600000	200	7854.55	1327.34	7445.11	2559.59	0.00	74.42	35.49	45.75	3.91	3.99	2.08	0.00
35000	600000	400	10825.83	2012.35	7986.77	2017.93	0.00	79.83	39.28	51.63	4.96	3.99	1.49	0.00
35000	600000	600	11601.48	2237.22	8102.56	1902.14	0.00	80.99	39.28	52.91	5.26	3.99	1.37	0.00
35000	600000	800	11927.98	2345.04	8145.19	1859.51	.00	81.41	39.28	53.33	5.38	3.99	1.33	0.00
35000	600000	1000	12123.00	2413.79	8167.38	1837.32	0.00	81.64	39.28	53.58	5.45	3.99	1.31	0.00

TABLE B.4 Results of MINSUN Simulation for High-Temperature Distribution Using Unglazed Collectors (Hartford, Conn.)

MINSUN Simulation Results: Hartford / Unglazed / High Temperature

AREA m^2	VOLUME m^3	BORE-HOLES	COLL SUPPLY MWH	STORAGE LOSS MWH	STORAGE SUPPLY MWH	HP ENERGY MWH	AUX ENERGY MWH	SOLAR FRACTION %	STORAGE TMIN C	STORAGE TMAX C	HP COP	HP COND MAX PWR MW	HP MTR MAX PWR MW	AUX MAX PWR MW
10000	200000	200	4444.06	111.78	4375.62	5252.69	376.40	43.74	9.20	27.57	1.83	3.89	3.75	3.99
10000	200000	400	4818.29	117.62	4740.55	5084.68	179.47	47.38	8.53	29.18	1.93	3.99	3.92	3.79
10000	200000	600	4927.01	124.21	4829.18	4996.05	179.47	48.27	8.39	29.53	1.97	3.99	3.87	3.79
10000	200000	800	4978.49	129.06	4866.05	4959.18	179.47	48.64	8.35	29.70	1.98	3.99	3.85	3.79
10000	200000	1000	4994.58	129.22	4881.85	4943.38	179.47	48.80	8.31	29.76	1.99	3.99	3.84	3.79
15000	200000	200	5081.57	232.34	4804.44	5109.30	90.96	48.02	10.67	31.17	1.94	3.99	3.84	3.79
15000	200000	400	5580.80	277.20	5256.06	4657.68	90.96	52.54	10.74	34.07	2.13	3.99	3.53	3.79
15000	200000	600	5774.51	305.31	5371.24	4542.50	90.96	53.69	10.74	34.72	2.18	3.99	3.48	3.79
15000	200000	800	5871.41	321.76	5421.44	4492.30	90.96	54.19	10.78	35.04	2.21	3.99	3.47	3.79
15000	200000	1000	5913.34	328.88	5445.13	4468.62	90.96	54.43	10.77	35.19	2.22	3.99	3.46	3.79
20000	200000	200	5381.26	279.34	5058.19	4855.54	90.96	50.56	11.86	33.55	2.04	3.99	3.68	3.79
20000	200000	400	6002.91	354.29	5604.35	4400.35	0.00	56.02	12.38	37.71	2.27	3.99	3.70	0.00
20000	200000	600	6271.52	401.87	5742.19	4262.51	.00	57.40	12.55	38.59	2.35	3.99	3.67	0.00
20000	200000	800	6408.33	428.54	5803.13	4201.57	0.00	58.00	12.67	39.06	2.38	3.99	3.66	0.00
20000	200000	1000	6477.24	442.40	5834.23	4170.47	0.00	58.32	12.71	39.28	2.40	3.99	3.65	0.00
25000	200000	200	5567.38	308.43	5219.16	4785.54	0.00	52.17	12.64	35.08	2.09	3.99	3.70	0.00
25000	200000	400	6300.88	409.84	5848.26	4156.44	0.00	58.46	13.61	40.36	2.41	3.99	3.55	0.00
25000	200000	600	6628.80	473.14	6000.89	4003.80	0.00	59.98	13.91	41.44	2.50	3.99	3.50	0.00
25000	200000	800	6802.28	509.14	6070.22	3934.48	0.00	60.67	14.12	42.02	2.54	3.99	3.48	0.00
25000	200000	1000	6896.72	529.97	6108.16	3896.54	0.00	61.05	14.22	42.33	2.57	3.99	3.47	0.00
30000	200000	200	5689.95	326.47	5324.45	4680.24	0.00	53.22	13.21	35.98	2.14	3.99	3.62	0.00
30000	200000	400	6510.91	450.70	6020.27	3984.43	0.00	60.17	14.54	42.28	2.51	3.99	3.44	0.00
30000	200000	600	6898.22	528.60	6183.94	3820.76	0.00	61.81	14.96	43.52	2.62	3.99	3.38	0.00
30000	200000	800	7105.41	572.93	6259.95	3744.75	0.00	62.57	15.23	44.19	2.67	3.99	3.35	0.00
30000	200000	1000	7219.65	599.31	6302.01	3702.69	0.00	62.99	15.38	44.56	2.70	3.99	3.33	0.00
35000	200000	200	5767.28	346.05	5401.95	4602.75	0.00	53.99	13.63	36.56	2.17	3.99	3.58	0.00
35000	200000	400	6696.92	496.17	6146.94	3857.76	0.00	61.44	15.28	43.68	2.59	3.99	3.34	0.00
35000	200000	600	7132.37	585.99	6317.10	3687.60	0.00	63.14	15.76	45.04	2.71	3.99	3.28	0.00
35000	200000	800	7364.07	637.11	6396.92	3607.78	.00	63.94	16.06	45.79	2.77	3.99	3.25	0.00
35000	200000	1000	7492.15	667.61	6440.67	3564.03	0.00	64.38	16.26	46.20	2.81	3.99	3.23	0.00
10000	300000	200	4616.23	111.18	4533.48	5284.45	186.76	45.31	10.97	24.54	1.86	3.89	3.70	3.99
10000	300000	400	5014.31	124.41	4934.55	4979.19	90.96	49.32	10.55	26.07	1.99	3.99	3.82	3.79
10000	300000	600	5153.40	135.43	5048.46	4865.27	90.96	50.46	10.42	26.45	2.04	3.99	3.74	3.79
10000	300000	800	5199.01	137.42	5091.16	4822.58	90.96	50.89	10.35	26.55	2.06	3.99	3.71	3.79
10000	300000	1000	5226.12	139.65	5113.66	4800.08	90.96	51.11	10.31	26.63	2.07	3.99	3.69	3.79
15000	300000	200	5282.92	248.18	4937.83	4975.91	90.96	49.36	12.78	27.79	1.99	3.99	3.79	3.79
15000	300000	400	5850.92	318.93	5486.96	4517.74	0.00	54.84	12.99	30.87	2.22	3.99	3.62	0.00
15000	300000	600	6097.60	357.54	5630.80	4373.90	0.00	56.28	13.00	31.56	2.29	3.99	3.57	0.00
15000	300000	800	6195.98	373.65	5687.72	4316.97	.00	56.85	13.01	31.81	2.32	3.99	3.56	0.00
15000	300000	1000	6257.91	384.98	5719.27	4285.43	0.00	57.17	13.02	31.98	2.34	3.99	3.55	0.00
20000	300000	200	5550.66	289.67	5178.02	4826.67	0.00	51.76	13.94	29.75	2.07	3.99	3.65	0.00
20000	300000	400	6264.69	408.35	5842.63	4162.07	0.00	58.40	14.76	34.26	2.40	3.99	3.40	0.00
20000	300000	600	6590.66	468.31	6002.83	4001.87	0.00	60.00	14.91	35.19	2.50	3.99	3.33	0.00
20000	300000	800	6740.85	498.59	6071.49	3933.21	.00	60.69	15.01	35.58	2.54	3.99	3.30	0.00
20000	300000	1000	6833.09	517.98	6109.19	3895.52	0.00	61.06	15.07	35.84	2.57	3.99	3.28	0.00
25000	300000	200	5720.84	315.58	5330.96	4673.74	0.00	53.29	14.74	30.96	2.14	3.99	3.55	0.00
25000	300000	400	6579.46	481.39	6100.34	3904.36	0.00	60.98	16.17	36.90	2.56	3.99	3.22	0.00
25000	300000	600	6975.30	560.51	6273.31	3731.39	0.00	62.70	16.43	38.02	2.68	3.99	3.14	0.00
25000	300000	800	7168.30	602.61	6350.57	3654.13	0.00	63.48	16.61	38.53	2.74	3.99	3.09	0.00

TABLE B.4 (Cont'd)

25000	300000	1000	7286.83	629.38	6392.54	3612.16	.00	63.90	16.72	38.86	2.77	3.99	3.07	0.00
30000	300000	200	5843.18	334.22	5436.91	4567.79	0.00	54.34	15.33	31.69	2.19	3.99	3.49	0.00
30000	300000	400	6818.89	540.38	6288.73	3715.97	0.00	62.86	17.32	38.85	2.69	3.99	3.09	0.00
30000	300000	600	7289.72	639.04	6473.29	3531.41	0.00	64.70	17.70	40.18	2.83	3.99	2.99	0.00
30000	300000	800	7520.13	691.32	6555.46	3449.23	0.00	65.52	17.93	40.79	2.90	3.99	2.94	0.00
30000	300000	1000	7664.33	725.70	6602.24	3402.46	0.00	65.99	18.09	41.19	2.94	3.99	2.91	0.00
35000	300000	200	5804.63	371.56	5560.50	4444.20	0.00	55.58	15.99	32.88	2.25	3.99	3.41	0.00
35000	300000	400	7623.25	747.63	6311.56	3693.14	0.00	63.09	17.58	39.01	2.71	3.99	3.07	0.00
35000	300000	600	7455.41	735.01	6624.39	3380.31	0.00	66.21	18.74	41.91	2.96	3.99	2.88	0.00
35000	300000	800	7719.21	796.37	6710.52	3294.17	0.00	67.07	19.03	42.61	3.04	3.99	2.82	0.00
35000	300000	1000	7889.90	837.71	6761.45	3243.25	.00	67.58	19.23	43.10	3.09	3.99	2.79	0.00
10000	400000	200	4722.59	209.22	4531.18	5286.76	186.76	45.29	12.02	22.42	1.86	3.89	3.73	3.99
10000	400000	400	5168.99	234.46	4960.28	4953.45	90.96	49.58	11.68	23.79	2.00	3.99	3.85	3.79
10000	400000	600	5322.35	250.59	5086.00	4827.74	90.96	50.84	11.56	24.15	2.05	3.99	3.76	3.79
10000	400000	800	5381.93	257.39	5137.31	4776.43	90.96	51.35	11.50	24.28	2.08	3.99	3.72	3.79
10000	400000	1000	5405.62	258.74	5160.53	4753.21	90.96	51.58	11.47	24.31	2.09	3.99	3.71	3.79
15000	400000	200	5403.92	243.66	4950.77	5053.92	0.00	49.48	14.01	25.46	1.98	3.99	3.82	0.00
15000	400000	400	6041.94	343.53	5571.72	4432.97	0.00	55.69	14.51	28.65	2.26	3.99	3.48	0.00
15000	400000	600	6316.73	388.06	5729.33	4275.37	0.00	57.27	14.54	29.31	2.34	3.99	3.41	0.00
15000	400000	800	6439.52	410.49	5796.70	4207.99	0.00	57.94	14.56	29.61	2.38	3.99	3.38	0.00
15000	400000	1000	6497.13	420.25	5828.25	4176.45	0.00	58.26	14.57	29.71	2.40	3.99	3.37	0.00
20000	400000	200	5607.64	388.37	5200.90	4803.80	0.00	51.99	15.22	27.45	2.08	3.99	3.68	0.00
20000	400000	400	6474.33	449.87	5939.80	4064.90	0.00	59.37	16.45	31.97	2.46	3.99	3.25	0.00
20000	400000	600	6841.95	519.78	6115.67	3889.03	.00	61.13	16.62	32.88	2.57	3.99	3.15	0.00
20000	400000	800	7020.63	557.44	6193.35	3811.35	0.00	61.90	16.73	33.32	2.63	3.99	3.11	0.00
20000	400000	1000	7113.73	577.42	6232.00	3772.69	0.00	62.29	16.80	33.53	2.65	3.99	3.08	0.00
25000	400000	200	5771.25	420.82	5340.26	4664.43	0.00	53.38	15.97	28.41	2.15	3.99	3.60	0.00
25000	400000	400	6806.09	625.44	6185.89	3818.82	0.00	61.83	17.87	34.40	2.62	3.99	3.08	0.00
25000	400000	600	7256.19	720.17	6370.75	3633.95	0.00	63.68	18.17	35.50	2.75	3.99	2.97	0.00
25000	400000	800	7479.60	771.56	6453.38	3551.31	0.00	64.50	18.35	36.05	2.82	3.99	2.91	0.00
25000	400000	1000	7605.87	802.05	6497.28	3507.41	0.00	64.94	18.46	36.34	2.85	3.99	2.88	0.00
30000	400000	200	5890.07	444.33	5438.65	4566.06	0.00	54.36	16.53	29.04	2.19	3.99	3.54	0.00
30000	400000	400	7068.53	696.95	6378.79	3625.91	0.00	63.76	19.13	36.37	2.76	3.99	2.94	0.00
30000	400000	600	7607.39	814.81	6575.34	3429.37	0.00	65.72	19.57	37.68	2.92	3.99	2.82	0.00
30000	400000	800	7881.71	879.81	6664.32	3340.38	0.00	66.61	19.84	38.33	3.00	3.99	2.75	0.00
30000	400000	1000	8039.03	918.55	6711.79	3292.92	0.00	67.09	20.00	38.68	3.04	3.99	2.72	0.00
35000	400000	200	5791.03	423.06	5615.97	4388.73	0.00	56.13	17.55	30.66	2.28	3.99	3.42	0.00
35000	400000	400	7825.90	844.18	6410.18	3594.51	0.00	64.07	19.43	36.59	2.78	3.99	2.92	0.00
35000	400000	600	7776.26	882.36	6744.16	3260.54	0.00	67.41	20.83	39.57	3.07	3.99	2.69	0.00
35000	400000	800	8087.49	957.24	6836.64	3168.06	0.00	68.33	21.15	40.31	3.16	3.99	2.62	0.00
35000	400000	1000	8275.42	1004.10	6887.82	3116.87	.00	68.85	21.36	40.72	3.21	3.99	2.58	0.00
10000	500000	200	4791.97	205.69	4516.68	5301.26	186.76	45.15	12.73	21.02	1.85	3.89	3.77	3.99
10000	500000	400	5263.91	237.94	4972.01	5032.68	0.00	49.70	12.51	22.32	1.99	3.99	3.87	0.00
10000	500000	600	5416.75	254.27	5102.00	4902.70	0.00	51.00	12.39	22.63	2.04	3.99	3.79	0.00
10000	500000	800	5482.95	262.17	5158.74	4845.96	0.00	51.56	12.34	22.76	2.07	3.99	3.75	0.00
10000	500000	1000	5515.83	266.68	5187.16	4817.54	0.00	51.85	12.31	22.83	2.08	3.99	3.73	0.00
15000	500000	200	5384.41	370.16	4964.94	5039.76	0.00	49.63	14.87	24.27	1.99	3.99	3.84	0.00
15000	500000	400	6103.72	480.25	5607.72	4396.98	0.00	56.05	15.50	27.22	2.28	3.99	3.41	0.00
15000	500000	600	6388.46	530.23	5768.63	4236.06	0.00	57.66	15.54	27.80	2.36	3.99	3.33	0.00
15000	500000	800	6526.76	557.45	5840.89	4163.80	0.00	58.38	15.56	28.08	2.40	3.99	3.29	0.00
15000	500000	1000	6599.69	573.06	5877.78	4126.92	0.00	58.75	15.59	28.23	2.42	3.99	3.27	0.00
20000	500000	200	5682.89	392.66	5184.40	4820.29	0.00	51.82	16.01	25.74	2.08	3.99	3.72	0.00
20000	500000	400	6595.74	613.06	5979.33	4025.36	0.00	59.77	17.55	30.41	2.49	3.99	3.16	0.00
20000	500000	600	6991.61	693.41	6161.51	3843.19	0.00	61.59	17.75	31.26	2.60	3.99	3.06	0.00
20000	500000	800	7192.33	738.33	6243.91	3760.79	0.00	62.41	17.87	31.69	2.66	3.99	3.01	0.00

TABLE B.4 (Cont'd)

20000	500000	1000	7306.35	765.38	6287.70	3716.99	0.00	62.85	17.94	31.93	2.69	3.99	2.98	0.00
25000	500000	200	5830.70	425.79	5320.31	4684.39	0.00	53.18	16.74	26.63	2.14	3.99	3.65	0.00
25000	500000	400	6992.63	672.62	6225.17	3779.52	0.00	62.22	19.09	32.64	2.65	3.99	2.99	0.00
25000	500000	600	7482.35	777.65	6417.40	3587.30	.00	64.14	19.42	33.71	2.79	3.99	2.87	0.00
25000	500000	800	7742.18	837.96	6506.11	3498.58	0.00	65.03	19.62	34.26	2.86	3.99	2.81	0.00
25000	500000	1000	7894.53	875.23	6554.14	3450.55	0.00	65.51	19.76	34.58	2.90	3.99	2.78	0.00
30000	500000	200	5944.61	450.50	5417.97	4586.73	0.00	54.15	17.30	27.23	2.18	3.99	3.59	0.00
30000	500000	400	7253.96	749.93	6419.11	3585.58	.00	64.16	20.41	34.55	2.79	3.99	2.85	0.00
30000	500000	600	7836.66	877.98	6618.76	3385.94	0.00	66.16	20.87	35.80	2.96	3.99	2.72	0.00
30000	500000	800	8144.48	951.33	6711.23	3293.46	0.00	67.08	21.14	36.44	3.04	3.99	2.65	0.00
30000	500000	1000	8330.90	997.93	6762.29	3242.42	0.00	67.59	21.32	36.82	3.09	3.99	2.62	0.00
35000	500000	200	5777.22	477.81	5636.21	4368.48	0.00	56.34	18.58	29.24	2.29	3.99	3.45	0.00
35000	500000	400	7978.74	924.76	6444.68	3560.01	0.00	64.42	20.63	34.73	2.81	3.99	2.83	0.00
35000	500000	600	8732.60	1101.74	6674.25	3330.45	.00	66.71	21.19	36.39	3.00	3.99	2.68	0.00
35000	500000	800	8211.64	1064.96	6907.77	3096.94	0.00	69.05	22.66	38.72	3.23	3.99	2.50	0.00
35000	500000	1000	8423.24	1118.76	6960.33	3044.37	.00	69.57	22.88	39.15	3.29	3.99	2.46	0.00
10000	600000	200	4844.86	196.97	4489.25	5328.69	186.76	44.87	13.16	19.99	1.84	3.89	3.81	3.99
10000	600000	400	5339.51	232.33	4961.12	5043.58	0.00	49.59	13.05	21.21	1.98	3.99	3.91	0.00
10000	600000	600	5495.62	251.44	5096.28	4908.41	0.00	50.94	12.94	21.50	2.04	3.99	3.83	0.00
10000	600000	800	5565.16	260.63	5156.16	4848.54	0.00	51.54	12.90	21.63	2.06	3.99	3.78	0.00
10000	600000	1000	5592.98	265.60	5184.35	4820.34	0.00	51.82	12.87	21.68	2.08	3.99	3.76	0.00
15000	600000	200	5433.16	369.20	4933.46	5071.24	0.00	49.31	15.34	23.08	1.97	3.99	3.89	0.00
15000	600000	400	6217.21	495.69	5606.99	4397.71	0.00	56.04	16.17	26.00	2.28	3.99	3.45	0.00
15000	600000	600	6512.43	550.67	5772.51	4232.19	0.00	57.70	16.22	26.54	2.36	3.99	3.31	0.00
15000	600000	800	6655.43	579.80	5846.51	4158.19	0.00	58.44	16.25	26.79	2.41	3.99	3.24	0.00
15000	600000	1000	6725.08	596.28	5883.07	4121.62	0.00	58.80	16.26	26.92	2.43	3.99	3.22	0.00
20000	600000	200	5726.12	389.63	5148.57	4856.13	0.00	51.46	16.47	24.47	2.06	3.99	3.77	0.00
20000	600000	400	6749.88	642.74	5988.32	4016.38	0.00	59.86	18.33	29.15	2.49	3.99	3.16	0.00
20000	600000	600	7169.99	731.43	6175.35	3829.35	0.00	61.72	18.55	29.96	2.61	3.99	3.00	0.00
20000	600000	800	7385.63	780.66	6260.47	3744.23	0.00	62.58	18.67	30.36	2.67	3.99	2.95	0.00
20000	600000	1000	7500.86	809.94	6304.58	3700.12	0.00	63.02	18.74	30.57	2.70	3.99	2.92	0.00
25000	600000	200	5878.86	426.42	5289.42	4715.27	0.00	52.87	17.23	25.37	2.12	3.99	3.69	0.00
25000	600000	400	7159.72	704.75	6233.70	3770.99	0.00	62.31	19.91	31.30	2.65	3.99	2.97	0.00
25000	600000	600	7696.82	822.20	6434.38	3570.31	0.00	64.31	20.28	32.34	2.80	3.99	2.82	0.00
25000	600000	800	7977.29	887.93	6525.63	3479.07	0.00	65.23	20.49	32.86	2.88	3.99	2.75	0.00
25000	600000	1000	8138.80	929.54	6574.69	3430.01	0.00	65.72	20.62	33.17	2.92	3.99	2.72	0.00
30000	600000	200	5988.36	452.73	5387.12	4617.57	0.00	53.85	17.79	25.95	2.17	3.99	3.64	0.00
30000	600000	400	7409.75	784.97	6425.84	3578.87	.00	64.23	21.24	33.14	2.80	3.99	2.82	0.00
30000	600000	600	8043.79	926.41	6632.62	3372.07	0.00	66.30	21.73	34.35	2.97	3.99	2.67	0.00
30000	600000	800	8377.59	1006.47	6727.63	3277.08	0.00	67.25	22.01	34.97	3.05	3.99	2.60	0.00
30000	600000	1000	8579.59	1058.45	6779.73	3224.97	0.00	67.77	22.19	35.35	3.10	3.99	2.56	0.00
35000	600000	200	5719.57	525.89	5663.72	4340.97	0.00	56.61	19.46	28.52	2.31	3.99	3.46	0.00
35000	600000	400	8031.51	978.80	6466.73	3537.97	0.00	64.64	21.54	33.48	2.83	3.99	2.79	0.00
35000	600000	600	8839.28	1169.09	6699.23	3305.47	0.00	66.96	21.90	35.07	3.03	3.99	2.62	0.00
35000	600000	800	9238.56	1269.45	6800.91	3203.79	.00	67.98	21.90	35.80	3.12	3.99	2.55	0.00
35000	600000	1000	8528.63	1216.11	6994.23	3010.47	0.00	69.91	23.92	37.86	3.32	3.99	2.39	0.00